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VOL. 52, PP. 1829-1840, 1 PL. DECEMBER 1, 1941

IGNEOUS ROCKS OF THE HIGHWOOD MOUNTAINS, MONTANA

PART V. CONTACT METAMORPHISM

BY E. S. LARSEN AND B. F. BUIE

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ABSTRACT OF PART V

Very near the contacts of the stocks the sediments have been replaced by sanidine and diopside, through magmatic reaction. An irregular zone of indurated sediments, produced largely by hydrothermal agents, extends outward from the stocks for as much as half a mile. Locally, more intense hydrothermal metamorphism has formed orthoclase and fibrous amphibole with some diopside and locally garnet, phlogopite, spinel, and cordierite.

Along the dikes metamorphism extends out from the contacts for a distance of a few inches up to 5 feet. Thermal metamorphism produced recrystallization of the fine interstitial material of the sandstone. Aegirite, calcite, hematite, and pyrite were deposited by hydrothermal solutions. Magmatic reaction produced diopside.

Reaction between sandstone and the magma of the headed dike caused progressive replacement of plagioclase and quartz by potash feldspar.

Granitic inclusions in the biotite phonolite dikes have a marginal shell in which plagioclase has been replaced by orthoclase. Surrounding each inclusion is a zone of mixed rock which contains quartz grains much embayed and surrounded by 0.1 mm. prisms of pyroxene.

GENERAL CONSIDERATIONS

The contact metamorphic effects in the rocks of the Highwood area have been produced by magmatic reaction, thermal metamorphism, and

hydrothermal metamorphism. Under hydrothermal metamorphism are included all the metamorphic processes accomplished by moving solutions, either liquid or gaseous.

The extent and metamorphism of sedimentary rocks adjacent to the stocks and dikes are unusually great for intrusive bodies of comparable size. In this area as elsewhere around intrusives of alkalic rocks, hydrothermal metamorphism is extensive. Sedimentary rocks around the stocks have been more metamorphosed than volcanic rocks in a similar position.

The slight degree of metamorphism around the laccoliths appears to have about the same character as that along the dikes.

The chief minerals produced by reaction are augite and orthoclase, which are the chief minerals of the igneous rocks. The chief minerals introduced by hydrothermal processes are augite, aegirite, orthoclase, and a fibrous amphibole.

METAMORPHISM ABOUT THE STOCKS

Around the stocks, the sediments have been much indurated by contact metamorphism over an irregular zone commonly half a mile in width. This is an unusually wide zone of metamorphism for such small stocks. In this zone the shales have been changed to hornfels, and the sandstones to quartzites. Pyrrhotite and pyrite are scattered throughout the rocks. A specimen of black hornfels from 0.4 mile below the contact with the stock in Shonkin Creek was originally a sandy shale. The microscope shows that the quartz grains have been little changed, but the clay matrix has been recrystallized to a very fine aggregate of sericite and undetermined minerals. The rock has numerous tiny veinlets and patches made up of quartz and epidote or quartz and a fibrous alkalic amphibole. There has probably been little change in bulk composition, yet conduction alone would hardly be adequate to carry the heat necessary for the metamorphism so great a distance from the contact, and moving solutions probably were required.

In many places, at the immediate contact, the sediments have been replaced by sanidine and diopside. A short distance from the contact remnants of quartz appear and outwardly increase in size and abundance. Within a few inches, at most, the rock is hornfels or quartzite. This type of replacement is probably due to a direct reaction of the magma on the sediments.

At a distance from the contact the clay matrix of the sediments has been recrystallized to hornfels. Pyrrhotite, pyrite, and some epidote, quartz, and fibrous amphibole are present chiefly in veinlets.

The hydrothermal metamorphism is extensive, as it characteristically is about intrusives of alkalic rocks. The mineralogy and general char-

FIGURE 2. SOFT DIKE OF BIOTITE PHONOLITE BETWEEN WALLS OF HARDENED SEDIMENTS
East of road from Geraldine toward Geyser, in small canyon in south edge of Shonkin Sag.

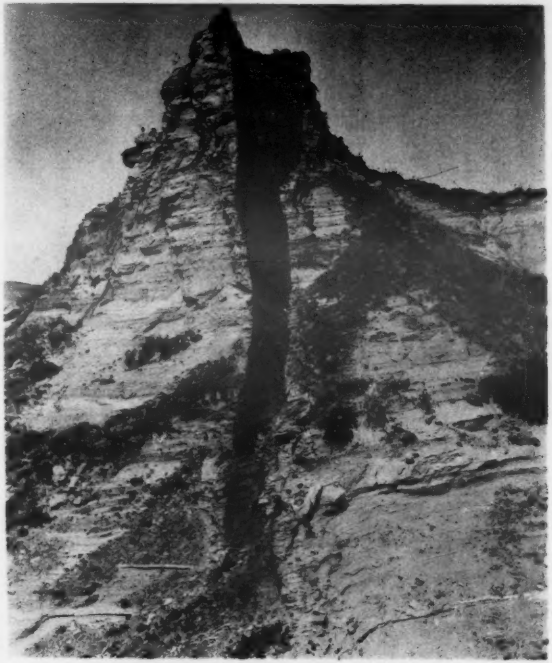

FIGURE 1. HARD DIKE OF PSEUDOLEUCITE MAFIC PHONOLITE WITH BORDERING INDURATED SEDIMENTS
East of road from Geraldine toward Geyser and south of Shonkin Sag.

VIEWS SHOWING HARDENING OF SEDIMENTS NEXT DIKES

acter of the metamorphism is much like that found associated with femic alkalic rocks at the Fen District, Norway (Brögger, 1921, p. 150-189), Iron Hill, Colorado (Larsen, in press), Libby, Montana (Larsen and Pardee, 1929), and elsewhere that are made up of green diopside grains with patches of fibrous amphibole. The hornfels is made up of potash feldspar and fibrous amphibole with some diopside. Veinlets of pyroxene cut the hornfels.

An unusual specimen from near the contact of the Middle Peak stock is millimeter-grained and made up chiefly of pyroxene with some birefracting garnet and a considerable amount of pale-green phlogopite growing about the other minerals and carrying patches of small, dark-green spinels. Some small inclusions in the shonkinite are made up of pyroxene, orthoclase, and garnet. Locally fractures in the hornfels are filled with martite or with actinolite.

Abundant cordierite forms the matrix between quartz grains in a thin section of a rock found near the White Wolf stock.

METAMORPHISM ASSOCIATED WITH THE DIKES

DESCRIPTION

The extent of the metamorphism of sandstone, shale, and fragmental volcanic rocks along the contacts of dikes in the Highwood Mountains area is greater than that ordinarily associated with dikes of similar size. Where the Highwood dikes are intrusive into such rocks a hardened layer of quartzite or hornfels 2 to 6 inches wide commonly is present along each contact. Along many dikes this metamorphosed rock is more resistant than the dike and stands as a double wall a few inches or a few feet in height. Occasionally the metamorphosed zone along a single dike may be 1 to 2 feet wide, and widths up to 5 feet or more have been observed. In these widest zones of alteration the metamorphism is likely not to extend uniformly from the dike, and both the width of the zone and the intensity of the metamorphism show great variation. A typical outcrop of a dike of mafic phonolite with the hardened Cretaceous sediments adjoining it is shown in Figure 1 of Plate 1, and an outcrop of a dike of weak biotite phonolite which occupies a trench between walls of indurated sediments is shown in Figure 2 of Plate 1. In many localities in the mountains numerous and closely spaced dikes are intrusive into shale and sandstone, and the country rock is strongly metamorphosed with little or no indication of localization of metamorphism along individual dikes. One such locality is that on the ridge west of Smith Creek near the junction of the north and south forks of Highwood Creek. At that place sandstone as thoroughly metamorphosed as that usually found only within a few inches of a dike is present 25 feet from any intrusion.

On the ridge west of the upper part of Alder Creek in sec. 15, T. 20 N., R. 10 E., a dike of augite-pseudoleucite phonolite 5 feet wide is intruded into tuffaceous beds. A specimen 2 feet from the contact is porous and friable and shows no megascopic evidence of metamorphism. The principal constituents of the thin section are angular grains of quartz and plagioclase up to 0.3 mm. diameter and larger fragments of finer-grained igneous rock. Some metamorphism is suggested by the presence of about 2 per cent of biotite, but this may have been an original constituent of the tuff. A specimen 1 foot from the contact obviously has been affected; it is compact and nonfriable, though still somewhat porous. In thin section the quartz grains show about 0.01 mm. of additional quartz around the original margins, which are marked by inclusions. The fine interstitial material shows some coarsening but does not appear to have been entirely recrystallized. A specimen from the contact of the dike is a firmly bound, dense rock, with sharp edges that are not friable. In thin section the interstitial material shows a considerable degree of recrystallization, though it still is fine-grained. The quartz grains have 0.02 mm. of quartz around their original boundaries. Very fine-textured rock fragments originally present in the tuff have been recrystallized so that the grain size is about twice that of similar fragments in the rock 2 feet from the contact.

An inclusion of metamorphosed sandstone (FBD 71) from a dike of biotite phonolite in sec. 27, T. 21 N., R. 10 E., about 1.3 miles southeast of the buildings of Big Sag Land and Livestock Company shows the following features:

Megascopically the rock is a gray fine-grained metamorphosed sediment. Thin bedding (1 to 15 mm.) has become conspicuous by differential metamorphism. Light-gray beds alternate with medium- to dark-gray and greenish-gray beds. Under the microscope much of the material is still too fine-grained to identify. A few detrital grains of plagioclase with margins replaced by orthoclase (?) are present. No quartz can be recognized. Thin flakes of biotite 0.1 mm. long are recognizable in the coarser and in some of the finer bands; they parallel the bedding. Minute prisms of pyroxene occupy irregular but well-defined areas 0.10 to 0.05 mm. in diameter in the coarser bands. These areas have inner cores of sericite and calcite, while their outer portions are composed almost entirely of a fine mat of minute prisms of pyroxene. Also outside these areas, fewer pyroxene prisms lie embedded in a clear, low-index, weakly birefringent mineral, probably orthoclase. The pyroxene has one index near 1.700, another higher; extinction angle is near 45°. It is too fine to identify with certainty but it probably is diopside.

In the localities of more intense and extensive metamorphism garnet, pyrite, and hematite are locally present in grains coarse enough to be recognized in hand specimens, but generally the metamorphosed rock is dense-textured compact hornfels or firmly bound quartzite with no recognizable minerals. In much of the altered rock the presence of pyroxene is indicated by greenish streaks or by a greenish cast to the rock as a whole.

The degree of recrystallization varies, depending upon the grain size of the clastic rock and its distance from the igneous rock. In many places the finer interstitial material has been recrystallized, while the coarser grains show no change except possibly very slight recrystallization around their margins, or slight addition of material. In fine-grained rocks (0.1 to 0.2 mm.) the degree of recrystallization is as great as 80 per cent within a few millimeters of the contact, but it grades down to 50 per cent a few centimeters away. Coarser rocks usually show less recrystallization. However, the degree of metamorphism varies greatly, and quantitative generalizations are difficult.

The most commonly introduced minerals are biotite, magnetite, orthoclase, pyroxene, and calcite; occasionally garnet and specular hematite are present. Biotite is generally present, especially near the contact; it exists as brown flakes 0.05 to 0.20 mm. in length, interstitial to the other minerals. Magnetite is present as scattered irregular clusters of grains in the finer material and as individual grains in the margins of the coarser grains of quartz and feldspar. In one thin section (FBD 406) for half a millimeter from the contact a low index mineral, probably orthoclase, forms minute tablets or prisms which are closely matted and arranged in radial groups. Calcite forms scattered interstitial patches; within a few millimeters of the contact locally it constitutes several per cent of the rock.

The metamorphism around the igneous intrusions at Haystack Butte is unusually irregular in extent. A part of the pyroxene present is aegirite, which was not observed in the metamorphosed rocks adjacent to the dikes, but otherwise the metamorphism around this irregular body is similar to that associated with the dikes. Pyroxene, biotite, and calcite have been introduced; feldspar has been recrystallized and is now orthoclase. Within a few centimeters of the contact pyroxene constitutes 40 per cent of the metamorphic rock. This pyroxene is for the most part diopside. Farther from the contact, both in the firm fragments of sandstone and shale and along cracks and open spaces, fine needles of aegirite and fibrous aggregates of an amphibole related to the soda-tremolite group found in Iron Hill, Colorado, have developed. The prisms of diopside have been altered to aegirite around their margins.

The diopside forms radial to irregular aggregates embedded in a cloudy, low-index, weakly birefringent groundmass. Aegirite replaces margins of the diopside prisms and forms incrustations along cracks and walls of cavities. The biotite has the usual absorption formula, $Z > X$, although the biotite of the igneous rock of Haystack Butte has $X > Z$.

SUMMARY AND CONCLUSIONS

A review of the preceding descriptions suggests that thermal and hydrothermal metamorphism and magmatic reaction all have been active. The recrystallization of fine interstitial material in the clastic rocks might have been accomplished by either thermal or hydrothermal action, but the rapid decrease in degree of recrystallization with increasing distance from the contact is indicative of the former. The uniform coarsening of the texture of fine-grained rock fragments in the tuff beds could more reasonably be ascribed to thermal metamorphism. The addition of quartz around original grain boundaries could result from recrystallization of finer grains by either heat or moving solutions. The occurrence of calcite as scattered patches in the metamorphosed rock might result from the recrystallization of detrital calcareous material or from introduction by hydrothermal solutions. The extensive development of aegirite along fractures at Haystack Butte, and especially the crystallization of fine needles of this mineral projecting into open spaces, could have been produced only by hydrothermal or pneumatolytic agents. The presence of pyrite, hematite, and calcite along fractures associated with dikes must be ascribed to the same origin. The locally erratic character of metamorphism along dike contacts and the extensive metamorphism of all rock at some localities where dikes are numerous indicate hydrothermal activity. The crystallization of orthoclase, and especially its development to the exclusion of quartz in a rock which has the megascopic features of the usual sandstone of this area, could not have been produced without considerable transfer of material; this could have been accomplished by hydrothermal processes or by magmatic reaction. The extensive development of diopside in the metamorphosed sedimentary rock at its contact with the igneous rock at Haystack Butte, whereas the hydrothermal agents produce aegirite, suggests that diopside is a product of magmatic reaction.

METAMORPHISM ASSOCIATED WITH THE HEADED DIKE

GENERAL STATEMENT

Throughout its exposures the headed dike is intrusive into loosely consolidated feldspathic and argillaceous sandstone and sandy shale. The extent of metamorphism which it has produced in these rocks varies

along the strike and from the sides to the top of the body. A zone of hardened rock is generally present along the contact. The width of this zone varies from a few inches, as in the exposure at the County road, to as much as 2 feet where exposed at several localities east of the road. At several places unusually intense metamorphism has been produced in the sandstone over the top of the headed dike with the result that locally the upper contact is gradational and not readily discernible.

DETAILED DESCRIPTIONS

In the exposure at the County road the sharp upper contact is well shown. A thin section which includes this contact shows sandstone completely recrystallized to a mosaic of quartz and feldspar. A concentration of biotite is present in a 0.5 mm. wide zone along the contact, but elsewhere it constitutes less than 1 per cent of the rock. For 2 mm. from the contact the metamorphosed rock is more than 50 per cent potash feldspar, but beyond that, to the edge of the section 7 mm. from the contact, quartz is predominant, and potash feldspar merely fills in between the quartz grains.

An unusual type of metamorphosed rock is found in a small saddle east of the gulch ¾ mile east of the County road. At this place remnants of the sandstone roof show a gradation from igneous rock (fergusite) rich in pseudoleucite through feldspathic rock with some quartz into a metamorphosed sandstone which has the unusual feature of containing crystals of pseudoleucite 5 mm. in diameter, 5 to 10 cm. from the igneous rock.

Another unusual metamorphic rock lying over the top of the headed dike occurs on the ridge which extends eastward from the County road, about 1000 feet from the road. This rock (FBD 277) has the appearance of a porous sandstone with an unusual granular, pseudo-oölitic texture. Mineral aggregates forming nodules 1 mm. in diameter stand out prominently on the weathered surface. In thin section the rock is seen to be thoroughly recrystallized and composed principally of quartz and potash feldspar. The mineral aggregates consist of elongated grains of potash feldspar grouped in a crudely radial arrangement around and interspersed with grains of quartz. The central parts of some are stained and cloudy and indeterminable. The quartz shows sharp extinction and generally is clear except in the marginal areas of the grains where cracks are numerous; the margins are convexly scalloped which suggests that there has been an irregular growth of additional quartz. The orthoclase contains microscopic to almost submicroscopic intergrowths of quartz (?) producing a micrographic texture. Grain boundaries of the feldspar are indistinct, and extinction is not uniform. Plates or prisms of quartz

penetrate the micrographic intergrowths and extend as much as 0.5 mm. through several of these units. An individual plate does not extinguish as a unit but in segments. These plates probably represent tridymite which has inverted to quartz.

A specimen of metamorphosed sandstone (FBD 292) from a roof pendant was collected 600 feet west of the end of the long exposure of the headed dike 2 miles east of the County road. It is composed principally of a mosaic of quartz grains 0.3 mm. in diameter. Outlines of grains are irregular. The rock has been thoroughly recrystallized, except possibly the central portion of the quartz grains. About 1 or 2 per cent of the rock is composed of platy quartz pseudomorphic after tridymite (?), as described above. Interstitial to these plates there is about 1 per cent of potash feldspar. The metamorphism of the sandstone to quartzite extends more than 18 inches from the contact.

Three specimens of metamorphosed sandstone were collected from the sides of the headed dike. These show a lower degree of recrystallization than the specimens from the top contact. A specimen (FBD 346) from an 8-inch thick slablike inclusion at the south contact of the headed dike 700 feet east of the west end of the long exposure east of the County road is composed chiefly of quartz and plagioclase in 0.1 to 0.2 mm. grains. No original grain outlines can be distinguished, but irregular scalloped margins indicate at least partial recrystallization. The plagioclase grains show clear unaltered central portions which grade outward through a clouded, partially altered zone to clear potash feldspar. Strongly dichroic plates and irregular grains of biotite up to 0.1 mm. in length constitute 2 per cent of the section. Very slender needles of apatite up to 0.2 mm. in length penetrate the biotite, quartz, and feldspar. Another contact specimen (FBD 284), originally composed of 0.3 mm. grains of quartz and plagioclase with some finer interstitial grains, shows recrystallization of the finer material and the margins of the 0.3 mm. grains within 25 mm. of the contact, and 50 mm. away even the fine interstitial material is not entirely recrystallized. Low-index feldspar molding between the original grains of quartz and plagioclase constitutes about 10 per cent of the rock within 25 mm. of the contact, but it progressively diminishes with increasing distance from the contact. Within 30 mm. of the contact small flakes and shreds of biotite make up about 5 per cent of the rock. The third contact specimen (FBD 326) is from the south side of the headed dike, 1400 feet east of the County road. It is from nearer the feeder of the headed dike than either of the other two specimens; the feeder, by projection from its exposure less than 100 feet to the east, must be present not more than 10 feet north of the location of this specimen. In hand specimen the contact is generally definite and clearly visible, but locally

indistinct bands of darker rock containing small pyroxene crystals extend into the quartzite; where the contact is sharp crystals of pale-green diopside 2 mm. long are common in the quartzite several millimeters from the igneous rock. In thin section one sees that the original character of the sandstone has been profoundly changed. The igneous rock is readily distinguished from the metamorphosed sedimentary rock by the presence in the latter of abundant 0.05-mm. stubby crystals and smaller rounded grains of pyroxene. Individual crystalline units of sanidine continue uninterruptedly across the contact. The original minerals of the sandstone have been entirely replaced, with the exception of isolated grains of quartz which remain to constitute less than 5 per cent of the metamorphosed rock.

Two small inclusions of metamorphosed sandstone a few inches in diameter show a high degree of alteration. One specimen (FBD 293), found in the shonkinite, is composed of 0.1-mm. grains of quartz, 0.02-mm. rounded grains and stubby prisms of diopside, and interstitial potash feldspar; it appears to have been entirely recrystallized. For perhaps 5 mm. from the igneous contact orthoclase completely takes the place of quartz, but farther into the metamorphosed rock quartz becomes an important constituent, and orthoclase merely fills in between the quartz grains. This relationship continues to the edge of the thin section, some 30 mm. from the contact. The thin section as a whole shows the approximate percentages: diopside 40, quartz 30, orthoclase 30. The other specimen (FBD 275), found in the fergusite, contains coarser grains of quartz averaging about 0.3 mm. with some as large as 1 mm. There are no indications of detrital grain boundaries, and even the coarest grains may have been entirely recrystallized; certainly their margins have been. Orthoclase is interstitial to the quartz and makes up about 5 per cent of the rock. Adjacent to the quartz grains and extending into the surrounding orthoclase are very thin 0.2-mm. long prisms or plates of a mineral which appears to be quartz pseudomorphic after tridymite. Over a given area the plates extinguish with the adjacent quartz grain. In addition to possibly containing inverted tridymite, this inclusion differs from the other in containing a little biotite and only 1 or 2 per cent of diopside. The fact that the inclusion found in the pyroxene-rich rock contains 40 per cent of diopside and the one found in the pyroxene-poor rock only 1 or 2 per cent may be significant, but the number of inclusions seen is not sufficient to warrant drawing positive conclusions.

SUMMARY

The typical contact effect of the headed dike upon adjacent feldspathic sandstone shows a progressive replacement by orthoclase of (1) the fine

detrital material interstitial to the coarser grains, (2) the margins of the coarser detrital plagioclase feldspar and quartz grains, and (3) all of the plagioclase and much of the quartz. The close relationship between nearness to the contact and degree of replacement indicates that reaction between the sandstone and the magma is responsible for this substitution of potash feldspar for the original minerals of the sandstone.

The following facts suggests that magmatic reaction rather than thermal or hydrothermal metamorphism is responsible for the development of diopside: (1) The igneous rock in the upper part of the headed dike is felsic, rich in pseudoleucite, and poor in pyroxene; the metamorphosed sandstone in contact with this rock contains no diopside. (2) abundant diopside developed in sandstone which was in contact with the lowermost part of the headed dike where augite is a principal constituent of the igneous rock, and near the feeder where more heat would have been available. (3) an inclusion of metamorphosed sandstone in the augite-rich lower rock of the headed dike contains 40 per cent of diopside, while a similar inclusion from the felsic upper rock contains only 1 or 2 per cent of diopside.

The unique spheroidal masses of radial aggregates of orthoclase tablets around quartz in porous sandstone can more reasonably be attributed to hydrothermal metamorphism than to either thermal metamorphism or magmatic reaction.

If the tabular units of quartz are pseudomorphs after tridymite, as they appear to be, the crystallization of that mineral may have resulted from thermal metamorphism. But the fact that this tabular quartz is not typical, being developed only at restricted places in sandstone which is in contact with or included in pseudoleucite-rich rock, suggests that volatile emanations may have had a part in the crystallization of tridymite.

The apatite must represent some introduction of material. The concentration of biotite near the contact indicates that thermal metamorphism alone is not responsible for crystallization of that mineral. The occurrence of pseudoleucite in sandstone 5 to 10 cm. from the igneous rock is difficult to explain. Mechanical mixing does not appear to have been responsible, although there has been some fragmentation of sandstone at this locality. Certainly some material was introduced, but whether by magmatic reaction or by moving solutions cannot be ascertained.

METAMORPHISM OF GRANITIC INCLUSIONS IN THE DIKES

Inclusions of light-colored granitic igneous rocks are common in the biotite phonolite dikes. These inclusions have the composition of grano-

diorite or quartz diorite and are granitoid to gneissic in texture. They are unlike any rock exposed in the Highwood Mountains area and must have been derived from a depth of several thousands of feet below their present position. A diameter of 3 inches to 6 inches is usual, though inclusions more than 12 inches in diameter have been observed. They range from spheroidal to elongate oval to tabular; edges and corners are well rounded. In each inclusion a thin marginal shell half an inch thick has been recrystallized, but the central portion for the most part shows no change.

Quartz and plagioclase feldspar are the principal constituents of these inclusions, and in the marginal zone of each inclusion plagioclase has been much more affected than quartz. The normal dike rock contains no quartz, but around some inclusions selective attack of plagioclase has left a narrow enveloping zone of mixed rock which contains numerous particles of quartz. These remnants of quartz are smoothly embayed, and surrounding each is a closely spaced aggregate of 0.1-mm. prisms of pyroxene. For 1 cm. from the margin of the inclusions inward the plagioclase has been replaced by potash feldspar along cracks and around margins of grains. The maximum width of this replacing fringe of orthoclase is about 0.1 mm. and it decreases toward the inner margin of the altered zone. Occasionally an original grain of plagioclase will persist only as a clouded core in an area of orthoclase, the latter showing a newly developed crystal outline. In some specimens, in addition to this fringe of orthoclase on the plagioclase, 0.1-mm. prisms or tablets of orthoclase have developed interstitial to the quartz, plagioclase, and other minerals.

Another type of replacement occasionally seen is one in which very fine flakes of biotite and minute grains of magnetite have been introduced along cleavage directions in the plagioclase. Biotite has also crystallized between the quartz and feldspar grains and to a slight extent along cracks within the quartz. Other minerals introduced in minor and varying amounts include calcite, sericite, slender prisms of green pyroxene (aegirite ?), and radial aggregates of fine prisms or needles of an undetermined mineral (specimen FBD 472). The uniform nature of the change produced in the marginal zone of each inclusion, and the partial replacement of plagioclase by feldspar which is more like the feldspar of the dike rock indicate that reaction between the dike magma and the inclusions has been more important than thermal or hydrothermal metamorphism. The lack of more penetrative alteration in the inclusions is attributable to the constant removal of the outer layer, while reaction with magma continued, and to the slowness of diffusion.

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Manuscript received by the Secretary of the Society, March 26, 1940.

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IGNEOUS ROCKS OF THE HIGHWOOD MOUNTAINS, MONTANA

PART VI. MINERALOGY

BY E. S. LARSEN, C. S. HURLBUT, JR.,
B. F. BUIE, AND C. H. BURGESS

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1. Photomicrographs of monticellite and leucite	1846

ABSTRACT OF PART VI

The minerals of the igneous rocks of the Highwood Mountains are described. The primary hornblende of the quartz latites is basaltic and it has been partly replaced by a common green hornblende. Hornblende is rare in the alkalic rocks. Augite is an abundant mineral of the alkalic rocks; in the syenites it contains some acmite, especially on the borders of the crystals. Aegirite is a common metamorphic mineral. The olivine of the shonkinites contains from 12 to 22 mol per cent of fayalite, that of the syenite from Square Butte 50 per cent. Monticellite twinned into trillings on (031) is an abundant mineral in one small intrusive body. In the alkalic rocks barium sanidine is abundant and plagioclase rare; leucite, primary analcime, and pseudoleucite are common and sodalite rare. Natrolite, thomsonite, and other zeolites are widespread and very abundant.

AMPHIBOLES

Primary amphiboles are the chief mafic minerals in the quartz latites and the few associated small intrusives. They are entirely lacking in the young mafic phonolites. They are present in a few of the syenites of the

TABLE 1.—*Optical properties of amphiboles from the Highwood Mountains, Montana*

	1	2	3	4	5	6	7	8
α	1.679	1.663			1.697	1.672	1.680	
β	1.700	1.675	1.650	1.69	1.713	1.686	1.692	1.643
γ	1.719	1.684			1.723	1.695	1.700	1.654
2V	80°	65°	45°	75°	55°	75°	Large	
$Z \wedge C$	3½°	15°	14°	30°	14°	15°	22°	20°
Pleochroism								
α	Light yellow green	Light yellow green	Straw yellow	Yellow	Light brown	Yellow green	Yellow	
β	Brownish yellow	Brownish green				Light green	Deep green	
γ	Dark reddish brown	Deep brownish green	Dark green	Very dark green	Dark brown	Dark green	Deep green	
Opt. Char.	–	–	–	–	–	–	–	

1. Basaltic hornblende from the quartz latite (FBH 55).
2. Green hornblende from the quartz latite (FBH 55).
3. From the white syenite of Highwood Peak stock.
4. From the gray syenite of Middle Peak stock.
5. From the syenite of Square Butte laccolith. Analyzed.
6. From a syenite dike.
7. From the dike of amphibole phonolite of Cottonwood Creek.
8. Metamorphic hornblende from a joint in metamorphosed sediments.

stocks, dikes, and sills and are uncommon in the laccoliths. They are likewise uncommon deuteric or hydrothermal minerals.

The primary amphibole of the quartz latites was a deep-brown basaltic hornblende whose optical properties are fairly uniform, although the crystals commonly show some zoning, as indicated by the difference in color, birefringence, and indices of refraction. The optical properties of a typical basaltic hornblende are given in column 1 of Table 1. These hornblendes are present as phenocrysts and are always more or less resorbed. They are also more or less replaced by a light- to bright-green hornblende. This replacement is believed to be paulopost as shown in the rock description. The optical properties of the green hornblende are fairly constant, and those of a typical specimen are shown in column 2 of Table 1. Amphiboles are rare in the stocks but are present in the white syenite of the Highwood Peak stock. The optical properties of the amphibole from the Highwood Peak stock are shown in column 3, and those for an amphibole from a massive gray syenite from the Middle Peak stock in column 4.

In the laccoliths amphibole was found only in the upper part of the syenite of Square Butte and in the thin stringer of syenite that cuts the transition rock of Shonkin Sag laccolith.

An analysis of barkevikite, which is an abundant mafic mineral in the upper sodalite syenite of Square Butte, was made by W. H. Melville for

TABLE 2.—*Analyses and ratios of amphibole from Square Butte*

		Molecular ratios	O	Ratios Bases	O to 24
SiO_2	38.41	640	1280	640	615
Al_2O_3	16.39	161	483	322	309
Fe_2O_3	3.75	23	69	46	44
FeO	21.75	304	304	304	292
MgO	2.54	63	63	63	60
CaO	10.52	188	188	188	181
Na_2O	2.95	48	69	138	132
K_2O	1.95	21			
H_2O	.24	14	14	28	27
TiO_2	1.26	16	32	16	15
MnO	.15				
	99.91		2502		

(Ca Na)	(Mg Fe^{II} Fe^{III} Al^{III})	(Al Si Ti)	0	(O (OH)
1.8 1.3	.6 2.9 .4 1.4	1.7 6.1 .2	22	1.7 .3
3.1	5.3	8		2

Lindgren and is quoted in Table 2. The optical properties of all the amphibole in this syenite are the same, and the optical data given in column 5 of Table 1 were measured by C. S. Hurlbut, Jr.

PYROXENES

Augite, a common phenocryst in the older quartz latites, is everywhere associated with biotite and hornblende. It forms only a few per cent of the average rock of this group. Its optical properties are: $\alpha = 1.682$, $\beta = 1.690$, $\gamma = 1.710$, 2V about 60°.

Augite is present in nearly all the younger group of volcanic rocks and is abundant in most. In most of the rocks and in the average rock it is exceeded only by the orthoclase and it makes up approximately 25 per cent of the average rock. Augite is one of the chief phenocrysts in nearly all the porphyritic rocks and it is also present in the groundmasses. Well-formed phenocrysts are not uncommonly a centimeter or more in length. The augites are pale green and characteristically zoned with recurrent zones of somewhat different color and extinction angle but with not much difference in composition. Hour-glass structure is fairly common. In a few of the rocks the augite crystals have a narrow border or a little irregular growth of aegirite about the crystals.

The augites show a remarkable uniformity in their optical properties in nearly all the rocks. About 40 pyroxenes from a variety of the shonkinites and related rocks of both the stocks and the laccoliths showed no appreciable variation and had the following optical properties: $\alpha = 1.692$, $\beta = 1.699$, $\gamma = 1.720$, 2V near 60°, Z ∧ c near 45°. The pyroxene pheno-

TABLE 3.—*Analyses of pyroxenes*

	1	2
SiO_2	49.42	49.66
TiO_2	0.55	.10
Al_2O_3	4.28	5.77
Fe_2O_3	2.86	5.00
FeO	5.56	7.10
MnO	0.10	.01
MgO	13.58	13.03
CaO	22.35	20.78
Mn_2O	1.04	.55
K_2O	0.38	.11
H_2O	0.09	.10
	100.21	102.31*

* ZrO, Cr_2O_3, BaO, Li_2O none, CO_2, .04, SrO tr., V_2O_3 .06.

crysts of the dikes and lavas gave slightly higher indices of refraction. In 15 rocks they had $\alpha = 1.703$, $\beta = 1.710$, $\gamma = 1.729$; in four rocks β was 1.706; and in six as low as 1.699. The pyroxenes in the syenites have somewhat higher indices of refraction—up to $\beta = 1.72$—and in a pegmatite dike that cuts the syenite of Highwood Peak $\beta = 1.771$, and the mineral is aegirite.

An analysis of a pyroxene from the shonkinite of Square Butte is quoted from Pirsson in column 1 of Table 3. In column 2 is given the analysis of a pyroxene from an essexite (3216P) rich in iron, from Prospect Hill, N. S. Wales, Ningaye, analyst.

The chief pyroxenes of the metamorphosed sediments are diopside and aegirite with $\beta = 1.747$, $\gamma = 1.782$. As is common elsewhere, aegirite appears to be chiefly deuteric or hydrothermal.

No orthorhombic pyroxenes were found in the late igneous series.

OLIVINES

Olivine, including its alteration products, is entirely absent from the older volcanic rocks, the quartz latites.

Olivine is present in nearly all the mafic rocks of the younger igneous group but it is uncommon in the light-colored members, including the syenites, nepheline syenites, and biotite phonolites. It makes up somewhat less than 10 per cent by weight of the average younger igneous

rocks. In the porphyritic rocks it is present chiefly as phenocrysts, and in a few of the dikes the amber-yellow olivine grains are 5 millimeters or more in length.

The optical properties of the olivines vary much more than do those of the common pyroxenes, and the indices of refraction of the pyroxenes do not tend to increase with those of the olivines. In the stocks the common range of the β index of refraction is from 1.677 to 1.698 indicating from 12 to 22 molecular per cent of fayalite. In the coarse-grained shonkinite of the small intrusive on the ridge between Middle and Highwood Peaks $\beta = 1.723$, indicating 34 molecular per cent of fayalite.

In the shonkinites of the laccoliths the olivines are rather uniform. Olivine in a specimen from 400 feet above the base of Square Butte has $\beta = 1.714$. The rare olivine in the mottled rock at the base of the syenite of Square Butte has 50 molecular per cent of fayalite as indicated by the following optical properties: $\alpha = 1.749$, $\beta = 1.760$, $\gamma = 1.773$.

In the extrusive rocks and the dikes β ranges from 1.672 to 1.702, for the most part near 1.685, indicating about 16 molecular per cent of fayalite. There is an indication that in rocks with a large amount of coarse olivine the iron content of the olivine is low. The olivine of the monticellite peridotite of Haystack Butte is unusually poor in iron as $\alpha = 1.651$, $\beta = 1.669$, $\gamma = 1.689$, indicating 9 molecular per cent of fayalite.

Some of the olivine crystals show zoning with appreciable range in composition.

The olivine in most of the rocks is in better-formed, less-resorbed crystals than is usual in basaltic rocks. In the alnoites and some other mica-rich rocks it is much resorbed and enclosed in or bordered by mica. In a few of the mafic phonolites and shonkinites the olivine has reaction rims of green or brown biotite. In some specimens the olivine is bordered by magnetite dust, beyond which is coarse brown biotite, all surrounded by a rim of green biotite. In other specimens a layer of pyroxene grains separates the olivine from the biotite.

The olivines are fresh in some of the rocks but in most of them they show more or less alteration to brown iddingsite or greenish serpentine. In many of the rocks the olivine is completely altered. In most of the porous reddened rocks with zeolites the olivine is largely or completely altered.

MONTICELLITE

Monticellite was found only in the monticellite peridotite of Haystack Butte about 3 miles northeast of Geraldine. Because of scattered patches of included amorphous material, it is slightly clouded in contrast with

the clear olivine with which it is associated. In thin sections it forms unique trillings in the shape of a six-pointed star divided into six segments (Pl. 1, fig. 1).

A sample of the monticellite containing about 1 per cent of the amorphous inclusions and a very little magnetite was separated by heavy solu-

TABLE 4.—*Analyses and optical data on monticellite*

SiO_2	36.67		
TiO_2	0.13	α=1.654±0.001	
Al_2O_3	0.75	β=1.664±0.001	
Fe_2O_3	0.10	γ=1.674±0.001	
FeO	7.57	Opt. −, 2V=82°±3°	
MnO	0.17		
MgO	21.11		
CaO	32.56	Theoretical molecules	
Na_2O	none	$CaMgSiO_4$	74.9
K_2O	0.25	$CaFeSiO_4$	19.1
H_2O+	0.15	$CaMnSiO_4$	0.4
BaO	0.18	$MgSiO_4$	3.4
SrO	0.08		98.6
	99.72		

tions. An analysis of this sample by Gonyer and the optical properties are shown in Table 4.

According to Bowen (1922), the monticellite from the alnoite of Isle Cadeaux has $\alpha = 1.653$, $\gamma = 1.668$. According to the data of Schaller (1935), the Haystack Butte monticellite is higher in FeO and FeO + MnO than any other analyzed monticellite. Its optical data fit fairly well on Schaller's Curve extended.

The optical orientation of the trilling pictured in Plate 1 is shown in Figure 1. The optical orientation of monticellite is given in the literature as $\alpha = b$, $\beta = c$, and this was found to be true for a crystal from Magnet Cove, kindly oriented by Professor Charles Palache. In Figure 1 the lines bisecting the points of the star are therefore the *c* crystal axes for the individual trillings. The angle between the traces of the faces forming the points of the star is 82° ± 1°. This is therefore the face (021). The composition and twinning plane is (031). The twinning of olivine into trillings on (031) has been described by Buri (1935), who concluded that calcium in the olivine strongly aids such twinning.

BIOTITE

Biotite is a common phenocryst in the older quartz latites. It has the following optical properties: $\alpha = 1.585$, $\beta = 1.648$, $\gamma = 1.650$, $2V = 5°$ to 20°, $r < v$ strong, pleochroism dark to light brown.

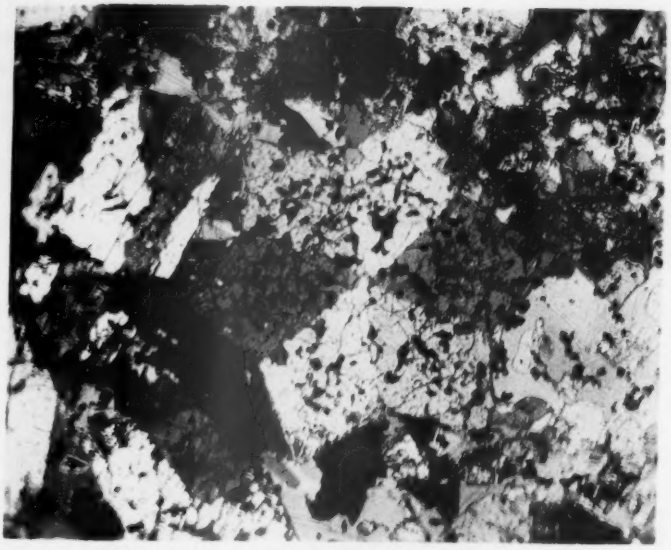

FIGURE 1. MONTICELLITE NEARLY NORMAL TO CRYSTAL AXIS, A showing star-shaped twins. Crossed nicols. X30.

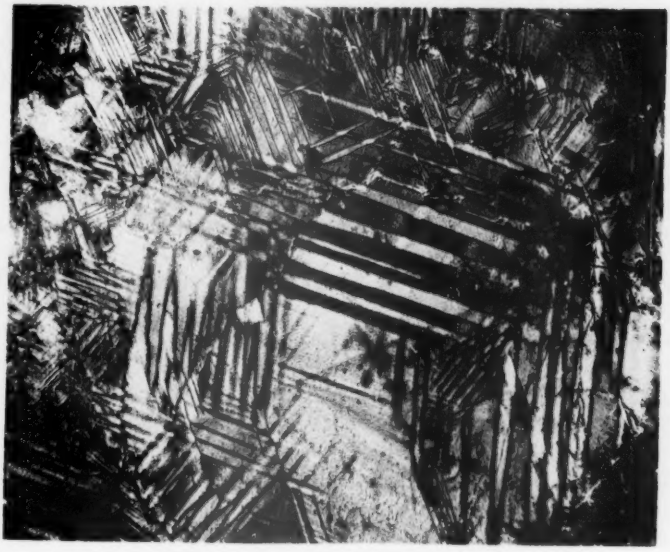

FIGURE 2. LEUCITE WITH POLYSYNTHETIC TWINS
Crossed nicols. X30.

PHOTOMICROGRAPHS OF MONTICELLITE AND LEUCITE

In the rocks of the younger series, biotite is a common mineral and makes something less than 5 per cent of the average rock. In the dike rocks biotite is present as phenocrysts in a small proportion of the mafic phonolites and is more common in the biotite phonolites and other femic

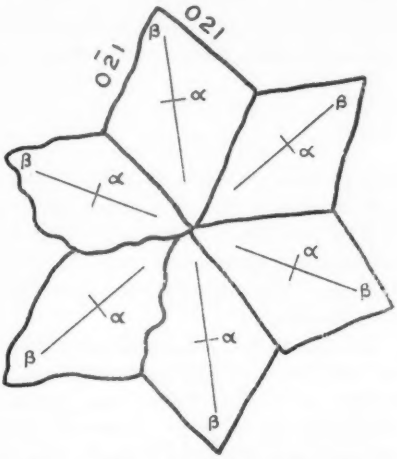

FIGURE 1.—*Optical orientation of monticellite twinned on (031)*

rocks. Some of the biotite is in plates a centimeter or more across. In some of the dike rocks biotite is the chief mafic mineral. Biotite is common and in some specimens abundant in the groundmasses. In the chilled border of many of the dikes the groundmass is very fine-grained and contains little or no biotite, while in the interior of the dike the groundmass is much coarser-grained and contains more or less biotite as a late mineral.

In the coarse-grained rocks of the shonkinite type, biotite is common; in the syenites and other felsic rocks it is one of the chief mafic minerals. In the alnoite and monticellite peridotite of Haystack Butte biotite is one of the chief minerals.

The biotites of the area show only a moderate range in the value of the β indices of refraction and for the most part have low values. The large porphyritic biotites in the minette-like rocks have cores that are light-colored and have low indices of refraction—β from 1.60 to 1.62—and irregular darker borders that have β about 1.63. Some of the biotites in the mica-rich minettes have β from 1.59 to 1.60. Biotite from 10 specimens of shonkinite and related rocks has $\beta = 1.635 \pm 0.004$. In the lavas

the value of β is near 1.63. The biotite of the alnoite of Haystack Butte has β near 1.62 ± 0.01; that in the monticellite peridotite has $\beta = 1.615$. The biotites of the later igneous series have very small axial angles and weak dispersion.

The difference between the pale, low-index biotite and the darker variety that has higher indices of refraction is probably due to the greater oxidation of the iron in the dark biotite rather than to a higher content of total iron.

FELDSPAR

DISTRIBUTION

In the older extrusive rocks—the quartz latites—feldspar makes about two-thirds of the rocks and is therefore about as abundant as in the average igneous rock or, perhaps, a little more abundant. In these rocks plagioclase, ranging from oligoclase to andesine, is the chief mineral and is in part in phenocrysts. The orthoclase and other alkalic feldspar are confined to the groundmass.

In the younger igneous rocks—the shonkinite-mafic syenite group—feldspar forms somewhat less than half the average rock, which is a much smaller proportion than is found in the average igneous rock. In these rocks sanidine, commonly carrying an unusually large proportion of barium, is far more abundant than plagioclase. The sanidine is present chiefly in the groundmass of the porphyritic rocks, in the pseudoleucite, and as a later mineral to crystallize in the granular rocks, but it is present as phenocrysts in some of the porphyritic rocks. Microcline and microperthite are rare in these rocks and are confined to the syenitic rocks.

Orthoclase is the chief feldspar of the Highwood Peak stock and it is one of the chief minerals formed in the contact metamorphism of the sediments.

Plagioclase is present in only a few per cent of the younger igneous rocks and, where present, it is with few exceptions in smaller amount than sanidine. It is therefore one of the minor constituents of the province. In the monzonite of Highwood Peak the plagioclase is oligoclase; in the extrusive rocks and the dike rocks it ranges from albite to labradorite. In a few of the lavas which have fine granular groundmasses, plagioclase is the chief feldspar.

SANIDINE, BARIUM SANIDINE, MICROCLINE, AND MICROPERTHITE

The feldspar of the phenocrysts and groundmass of the porphyritic rocks and of the granular rocks is a typical sanidine, glassy and with a small axial angle. It carries some barium. In the phenocrysts of the porphyritic rocks the mineral has the appearance of typical sanidine except that its mean index of refraction is commonly near or even greater

than that of Canada balsam. It shows some zoning with a few oscillatory zones, but the difference in composition between the different zones is not great. An analysis of a typical barium sanidine of this kind from an analcime mafic phonolite that has phenocrysts of clear analcime,

TABLE 5.—*Feldspar from the Highwood Mountains*

	1	2
SiO_2	57.80	64.39
TiO_2	0.17	0.09
Al_2O_3	21.55	18.81
Fe_2O_3	0.29	0.91
FeO	1.14	
MgO	0.72	none
CaO	1.35	0.39
Na_2O	3.71	0.98
K_2O	8.00	13.71
BaO	5.02	none
SrO		none
H_2O	0.21	0.45
	99.96	99.73
Formula	$Or_{50}Ab_{26}Ce_{13}$ An_7Cg_4	
α	1.536	1.519
β	1.542	1.523
γ	1.546	1.526
2V	48°	
$X \wedge c$	25°	
	Z=b	

1. Barium sanidine phenocrysts from the mafic phonolite (FBHL 114) cliffs at the base of the mafic phonolites 1½ miles N. 60° W. of Comb Butte. An analysis of the rock is given by Larsen (1941, column 6, Table 2).

2. Sanidine from pseudoleucite of pseudoleucite rock at the top of the headed dike along the road between Geraldine and Geyser. The analysis is of the part of the pseudoleucite that was insoluble in acid, and the microscope showed it to be nearly pure sanidine with less than 2% impurities, chiefly undissolved isotropic material (altered nepheline).

augite, serpentinized olivine, and barium sanidine in a fine groundmass made up of about the same minerals is shown in Table 5, column 1. The analyzed powder contained about 1 per cent of impurities.

Some of the phenocrysts show strong gradational zoning with cores richer in barium than the analyzed feldspar, grading to borders low in barium. The feldspar from the mafic leucite syenite (leucite malignite) in several small intrusives is very strongly zoned. This rock is made up about one third of fresh leucite, somewhat more of augite, a few per cent each of olivine and ore, and 10 per cent of interstitial sanidine. Adjoining the sanidine the leucite has been replaced to a small extent by a lacework of sanidine. The interstitial feldspar has cores rich in barium grading to the feldspar that replaces the leucite which is practically free of barium. The feldspar was divided into three nearly equal parts by

heavy liquids. The part with specific gravity greater than 2.87 had 16.45% BaO, according to F. A. Gonyer, indicating 41% of celsian. The core must be even richer in BaO. This grades to the feldspar that replaces the leucite which, from its density and optical properties, is free from BaO. Zoned interstitial feldspar similar to these was found in a moderate proportion of the porphyritic rocks.

The feldspar phenocrysts in the typical dark porphyritic rocks are nearly all rich in barium, but some of the groundmass feldspar appears to be nearly free of barium.

In the early stages in the replacement of leucite and analcime by feldspar and cloudy isotropic material, the feldspar is practically free of BaO. An analysis of such a feldspar from the pseudoleucite of the upper part of the headed dike is shown in Table 5, column 2. It shows no BaO or SrO and very little CaO and Na_2O. The indices of refraction of feldspar from many pseudoleucites (some were derived from analcime) were measured, and they are much alike, indicating that in the replacement of leucite and analcime to pseudoleucite the sanidine is free of BaO, even though the liquid that caused the replacement is rich in BaO. The available evidence indicates that they are very low in Na_2O as well.

In the interior of dikes and elsewhere, where the groundmass crystallized slowly, the feldspar of the pseudoleucite is also recrystallized and coarsened and in this recrystallization the feldspar is reworked so that the BaO is uniformly distributed in all the sanidine of the rock. The feldspar of the granular shonkinites is believed to be the final stage in this recrystallization.

Optical study of the sanidine of the granular rocks of the stocks shows that the barium content varies from practically 0 to 7 per cent or even more. The optical properties of the sanidine from four shonkinites and from the syenite of a narrow dike from the Shonkin stock and from a coarse shonkinite from the Middle Peak stock are: $\alpha = 1.518$, $\beta = 1.524$, $\gamma = 1.526$, $2V = 0°\text{-}30°$. These data indicate sanidine nearly or quite free of barium. The sanidine of three shonkinites from the Shonkin stock and three from the Arnoux stock, and the sanidine of the microperthite of a pegmatite dike of the Highwood Peak stock, has β about 1.530, indicating 4 per cent of celsian. The sanidine from two coarsely crystalline shonkinites, one from the Middle Peak stock and one from a small intrusive on the ridge between Middle and Highwood peaks, a mafic syenite from the White Wolf stock, a felsic syenite from Thane Mountain, and a mafic pseudoleucite-augite syenite from East Peak has $\beta = 1.534$, indicating about 7 per cent of celsian.

A porphyritic syenite from Highwood Peak has phenocrysts with 6 per cent celsian and matrix feldspar with 11 per cent celsian.

The feldspar of the laccoliths is all of the sanidine variety with 2V ranging from 1° to 5°. The β index of refraction was measured on sanidine from 12 different rocks and ranged from 1.519 to 1.530, probably indicating a variable barium content. There seems to be no systematic variation in the feldspar from the different rocks.

LEUCITE, PRIMARY ANALCIME, AND SODALITE

Fresh leucite was found as phenocrysts in a few per cent of the lavas and in fewer of the dike rocks. A few small intrusive bodies are made up largely of fresh leucite.

Glassy analcime occurs as phenocrysts in a somewhat larger number of lavas than does fresh leucite. It is chiefly as phenocrysts but grades to the groundmass.

The leucite and analcime are in crystals that look much alike and they are in rocks of essentially the same kind. In thin sections the leucite can in most cases be identified by its characteristic twinning (Pl. 1, fig. 2). In every rock the minerals were checked by an index of refraction measurement. The leucite has the index of refraction common to leucite (1.509); the analcime has an abnormally high index of refraction ($n = 1.493$).

An analysis of the leucite from the missourite of the Shonkin stock shows some water but has only a little soda (Table 6, column 1).

An analysis of the clear analcime from phenocrysts in a lava (FBH 169) of mafic leucite phonolite from the west end of the ridge of volcanic rocks which are east of the Geraldine Geyser road and west of Square Butte is given in column 2 of Table 6. This analcime has all the appearance under the microscope of being a fresh primary mineral and it is found only in the freshest rocks—rocks in which the olivine and other minerals show little alteration and which show no zeolites. This analcime is high in K_2O. It seems probable that at high magmatic temperature analcime is able to take considerable K_2O in solid solution, and this tends to confirm the evidence from the thin sections that these clear analcime phenocrysts are primary.

Two analyses of an analcime, believed by Lindgren (1886; 1890) to be primary, from a dike of analcime basalt in the Highwood Mountains are given in Table 6, columns 3 and 4.

Sodalite was found by Pirsson in a few of the dikes and other small intrusive rocks related to syenite, but the chief occurrence is in the upper part of the syenite of Square Butte (Table 6, column 6).

PSEUDOLEUCITE

Most of the pseudoleucite in the rocks of the Highwood Mountains is made up of a mixture of sanidine and a cloudy, amorphous material. In

some of the lavas, especially where altered, and in a very few of the other rocks natrolite or analcime takes the place of the amorphous material, and locally calcite and other alteration products are present. The sanidine has low indices of refraction ($\alpha = 1.518$, $\beta = 1.523$, $\gamma = 1.525$)

TABLE 6.—*Analyses of leucite, analcime, sodalite, and zeolites*

	1	2	3	4	5	6	7	8
SiO_2	54.46	51.41	54.90	49.87	56.00	41.56	42.43	44.85
TiO_2		none					none	none
Al_2O_3	22.24	23.03	23.30	22.55	21.27	29.48	30.11	27.94
Fe_2O_3	0.68	1.35	tr.	1.51	tr.	0.49	0.06	0.20
FeO								
MnO		none						none
MgO		0.43	0.70	1.28		0.15	none	none
CaO	0.10	1.19	1.90	2.62	0.33	0.49	3.24	2.00
Na_2O	0.70	8.48	10.40	10.92	5.16	19.21	9.61	14.47
K_2O	18.86	4.48	1.60	2.66	10.85	0.91	4.97	none
H_2O-	2.29	0.28	7.50	11.05	6.89	0.45	9.67	.51
H_2O+		9.32				3.73		10.17
SO_3			none	tr.	none			
Cl			none	none	none	4.79		
BaO								none
SrO								none
						101.26		
Less O for Cl +F						1.08		
	99.33	99.97	100.30	102.46	100.50	100.18	100.09	100.14
Sp.G.								2.285

1. Leucite from missourite at head of Shonkin Creek (Pirsson, 1905, p. 117).

2. Analcime (primary ?). Phenocrysts from an analyzed mafic analcime phonolite (FBH 169) from the west end of the ridge that is east of the Geyser-Geraldine road and west of Round Butte. F. A. Gonyer, analyst.

3 and 4. Analcime, believed by Lindgren (1886; 1890) to be primary, from a dike of analcime basalt.

5. White component from leucite shonkinite of East Peak; L. V. Pirsson (1905, p. 107).

6. Sodalite with some analcime from the upper sodalite syenite of Square Butte. Analyzed material contained some analcime. Quoted from Pirsson (1905, p. 68). W. H. Melville, analyst.

7. Amorphous, cloudy material from pseudoleucite of upper part of headed dike. Part soluble in acid. Analysis by F. A. Gonyer.

8. Natrolite high in H_2O. Nodules in a mafic phonolite ¾ mile south of North Peak. F. A. Gonyer, analyst.

and is low in sodium and barium. The clouded amorphous material has the composition of nepheline with water. It is crossed by cracks and has an index of refraction of 1.500.

A representative sample, using whole crystals, of the pseudoleucite was picked out from the pseudoleucite-rich rock in the upper part of the headed dike, and the extraneous material was carefully removed. A 2-gram portion of this pseudoleucite was treated with acid by F. A. Gonyer, and 66.0 per cent was insoluble. The insoluble fraction was examined under the microscope and found to be at least 98 per cent feldspar, and the chief impurity was undissolved amorphous material.

Both the feldspar and the solution containing the dissolved fraction were analyzed according to standard analytical methods with the results shown in Table 7.

The theoretical composition of leucite is given in column 4, and the difference between this and the pseudoleucite in column 5. The pseudo-

TABLE 7.—*Analyses of pseudoleucite*

	Part soluble in acid	Part insoluble in acid	Whole Pseudoleucite	Leucite	Difference
SiO_2	42.43	64.39	56.9	55.0	+1.9
TiO_2	none	0.09	0.1		
Al_2O_3	30.11	18.81	22.6	23.5	−0.9
Fe_2O_3	0.06	0.91	0.6		
MgO	none	none	none		
CaO	3.24	0.39	1.3		+1.3
Na_2O	9.61	0.98	3.9		+3.9
K_2O	4.97	13.71	10.8	21.5	−10.7
H_2O+	9.67	0.45	3.5		+3.5
BaO		none	none		
SrO		none	none		
	100.09	99.73	99.7		
Per cent of sample	34	66			

leucite has only about half as much K_2O as leucite, more soda and H_2O, and some more lime, but is otherwise very similar.

The detailed description and discussion of the origin of the pseudoleucite has been published by Larsen and Buie (1938), and only a brief statement will be made here.

Pseudoleucite was found chiefly in the phenocrysts of the porphyritic rocks, but it was found also in the groundmasses of some of them. It is not present in most of the granular rocks, as in the slow crystallization of such rocks it is commonly lost in the course of crystallization. Many, if not most, of the shonkinites and nepheline syenites originally had pseudoleucite, which has become a part of the granular rock. All stages in this recrystallization have been seen from pseudoleucite with submicroscopic texture to that with granular texture such that the pseudoleucite can be distinguished only as rounded patches that lack dark minerals, and finally to granular rocks. All the stages have been found in sections from the chilled borders to the centers of some of the dikes and laccoliths.

Photographs of pseudoleucite in the headed dike are shown by Buie (1941), those of pseudoleucite in the rocks of the stocks by Burgess (1941).

The pseudoleucite was formed from leucite or analcime for the most part after the magmas reached their present positions—after the intru-

sion of the dikes, sills, laccoliths, and stocks, but before complete crystallization of the rocks. The small amount of pseudoleucite that occurs as lacework around the margins of the fresh leucite is probably due to magmatic reaction, but most of the pseudoleucite is due to unmixing of a potash analcime or a soda leucite.

ZEOLITES

Zeolites are abundant and widespread in the younger igneous rocks, especially in vesicular lavas and porous tuffs. They fill vesicles, cement tuff, form veinlets, and replace leucite, analcime, nepheline, and other minerals. In the volcanic rocks irregular masses of zeolite that weigh over 100 pounds were found. Natrolite is the chief zeolite in the veinlets and vesicles, thomsonite is fairly abundant, and clear analcime is rather rare. The chief material replacing leucite and clear analcime is a cloudy, amorphous-looking material that has about the composition of nepheline with some potash and lime and much water or the composition of thomsonite. It might be called amorphous thomsonite. An analysis of this material from the pseudoleucite of the upper part of the headed dike southwest of Geraldine is shown in Table 7, column 1.

Natrolite is the most abundant zeolite filling open spaces, and very large irregular masses were found in some places. Fibrous natrolite also replaces analcime, leucite, nepheline, and other minerals. The coarsely columnar natrolite of the open space fillings is in large part ordinary natrolite with $\alpha = 1.479$, $\beta = 1.483$, $\gamma = 1.493$.

A mafic phonolite from ¾ mile south of North Peak has abundant white nodules up to 2 inches across of fibrous natrolite that has $\alpha = 1.489$, $\beta = 1.491$, $\gamma = 1.501$. An analysis of this natrolite given in column 8, Table 6, shows that it has one more molecule of H_2O than ordinary natrolite. A similar natrolite was collected from a syenite stringer in the headed dike.

The thomsonite is in coarse fibers and in a dozen specimens tested has approximately the following optical properties: $\alpha = 1.527$, $\beta = 1.530$, $\gamma = 1.540$, β parallel to elongation and α parallel to the best cleavage.

MISCELLANEOUS MINERALS

The apatite in all the igneous rocks is fluorapatite, and ω varies from 1.638 to 1.642.

Brown melanite garnet was found in small amount in a few of the rocks as a very late magmatic or hydrothermal mineral. A specimen from a hydrothermally altered igneous rock of the Middle Peak stock had an index of refraction of 1.82.

A green spinel, found in the same rock as the garnet just described, has an index of refraction of 1.78.

Thenardite is an abundant mineral precipitated from the lakes in the Shonkin Sag.

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IGNEOUS ROCKS OF THE HIGHWOOD MOUNTAINS, MONTANA

PART VII. PETROLOGY

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ABSTRACT OF PART VII

In the shonkinite series olivine, leucite, and analcime crystallized only from magmas with over 20 per cent of mafites. At this stage the leucite and analcime inverted to pseudoleucite. Pyroxene crystallized over the whole range of rocks and changed little in composition until the magma reached the composition of nepheline syenite when it became richer in aegirite. A little pale biotite crystallized early, but most of the biotite is dark and crystallized late. A little barium rich sanidine crystallized early. The abundant late feldspar is poor in barium.

Four petrographic subprovinces are represented in the area. The older quartz latites are near lime-alkalic rocks, the syenites and monzonites of Highwood Peak are somewhat farther removed, and the shonkinite series are potash-rich alkalic rocks. The alnoites are very rich in lime. The parent mafic magmas of the various subprovinces formed in depth by differentiation of a primary basaltic magma. These parent magmas were erupted toward the surface and there differentiated in a different way. The differentiation of the shonkinite magma was chiefly by settling of augite, olivine, and some biotite.

CRYSTALLIZATION AND TEXTURE

Mafic phonolite makes up nearly all the extrusive rock of the later volcanic series of the Highwood Mountains and over half the dikes, sills, and other small intrusive bodies. Shonkinites, which have the same chemical composition as the mafic phonolites, make up part of the laccoliths and the greater part of the stocks of the area. Since we have all stages in texture from porphyritic rocks with submicroscopic groundmasses to coarsely crystalline rocks, and some of the dikes and laccoliths show every gradation between these textures, we have an excellent opportunity to study the course of crystallization of the magma that formed the rocks.

Olivine, augite, and leucite (including analcime and their replacement products) are abundant as phenocrysts in nearly all the rocks with fine-grained groundmasses. Light-brown biotite and barium sanidine are present in phenocrysts in small amount in a few of such rocks. The olivine for the most part is in sharp crystals with little or no magmatic resorption, but in a few rocks it has been reacted on to form biotite. The augite and hyalophane are in sharp crystals, and both show oscillatory zoning. The biotite commonly shows much resorption and an outer zone of dark-colored biotite of the kind found in the groundmass. These phenocrysts must have been precipitated before the magma was intruded to its present position, as they are of about the same size and in about the same amount in the chilled borders as in the more coarsely crystalline rocks.

The augite, olivine, leucite, and analcime continued to crystallize in the groundmass but in decreasing amount. Olivine probably ended its crystallization early. Nearly all the feldspar formed after the magma was intruded as it is chiefly in the groundmass. In some of the granular rocks with leucite, analcime, or their alteration products, the feldspar molds about the leucite or analcime. This interstitial feldspar is rich in barium and is strongly zoned with cores that contain as much as 16 per cent of BaO. All the feldspar that crystallized directly from the magma is rich in barium. By the separation of this residual liquid a syenite or nepheline syenite rich in barium might be formed.

Dark-brown biotite is rather abundant in many of the rather coarsely crystalline groundmasses but is absent in most of the very fine-grained groundmasses. It is a much later mineral and may be largely a reaction mineral. Altered nepheline is found in the groundmass and in the pseudoleucite. Aegirite is a late mineral as it is found chiefly as a border about augite crystals in the felsic rocks.

A variety of recrystallizations and reactions took place in the magma. The most extensive of these was the formation of pseudoleucite from

leucite and analcime. This is believed to be due to unmixing rather than direct magmatic reaction. Another type of replacement of leucite and analcime by sanidine is no doubt due to magmatic reaction. In this, sanidine eats into the borders of the crystals. This reaction has replaced only a narrow zone of the leucite, even in the coarsely granular leucite or analcime rocks. The sanidine of both kinds of replacement is nearly free of barium, even where the interstitial feldspar is rich in barium.

In rocks with fine-grained groundmasses, the pseudoleucite is in sharply bounded crystals and is made up of fine intergrowths. As the groundmass becomes coarser, the pseudoleucite becomes coarser-grained and forms less sharply bounded crystals. In rocks with still coarser groundmass the pseudoleucite merges with the groundmass, and the barium is uniformly distributed in the feldspar of the groundmass and the pseudoleucite. In the final stages, all evidence of pseudoleucite is lost, and the resulting rock is a shonkinite. All gradations from a chilled zone of pseudoleucite mafic phonolite to granular shonkinite can be seen in some dikes, in the laccoliths, and especially in the headed dike.

Observations lead to the conclusion that leucite crystallized fairly early from a crystallizing magma of the composition of shonkinite or mafic phonolite and that it has only a short range of stability. By the time the liquid phase has the composition of a nepheline syenite rich in mafic minerals, leucite is converted to sanidine and nepheline. It crystallizes only from a mafic-rich magma. This may account for the general lack of leucite or pseudoleucite in the nepheline syenites and phonolites, although, except for the dark minerals, which are in small amount, the compositions of many of them are in the leucite field of the experimental system nepheline-kaliophlite-silica (Schairer and Bowen, 1935). The mafic constituents and the mineralizers appear to remove them from the leucite field.

The conditions that favored the formation of the porphyritic rocks with granular feldspar groundmasses is uncertain. It was probably in part rate of cooling, in part the composition of the magma or the content of mineralizer. The replacement of the olivine by biotite and magnetite is associated with these feldspar rocks.

The replacement of the analcime and leucite by cloudy material and of olivine by iddingsite are closely associated. They appear to have been earlier than the formation of the natrolite and other zeolites and were probably paulopost. The natrolite, thomsonite, and other zeolites may be late paulopost or weathering products. They are present in veins and patches in clastic rocks.

PETROGENESIS

INTRODUCTION

Larsen (1940) has discussed the petrographic province of central Montana, and only a brief statement will be made here. This province is defined to include the Tertiary igneous rocks near the eastern front of the Rocky Mountains or in the adjoining plains and from the Yellowstone National Park on the south to the Canadian Boundary on the north. Related rocks extend both to the north and south. Scattered over Central Montana are 12 major groups of mountains which contain Tertiary igneous rocks, and each group represents rocks from one or more centers of eruption. The rocks of one mountain group or the rocks erupted during a limited time in a mountain group differ from the rocks of other mountain groups or from the rocks erupted at another time in the same mountain group. The related rocks erupted during a limited time from one or more centers of eruption are said to belong to a subprovince.

The rocks of the subprovinces of the larger mountains range from mafic-rich to mafic-poor, but they have mineralogical and chemical peculiarities that distinguish them from the rocks of other subprovinces. Chemical analyses of the rocks of a subprovince, when plotted on a variation diagram, fall near regular curves, and these curves are characteristic of the subprovince.

The rocks at the felsic end of the variation diagrams are very similar for all the subprovinces that contain quartz-bearing rocks, but at the mafic end the rocks of one subprovince are different from those of the other subprovinces. The mafic rocks therefore characterize a subprovince better than the felsic rocks. The mafic rocks of the petrographic province of central Montana range from ordinary basalts and gabbros to orthoclase basalts and gabbros, to plagioclase shonkinite, and to shonkinite lacking plagioclase.

In the Highwood Mountains four subprovinces have been recognized.

QUARTZ LATITE SUBPROVINCE

The quartz latites are the oldest of the Tertiary igneous rocks. They are characterized by abundant plagioclase, quartz, and hornblende, minerals absent or rare in the shonkinites and related rocks. The quartz latites are all much alike. The one chemical analysis confirms the mineralogical data and shows that the rock is not far from an ordinary lime-alkalic rock but is high in K_2O and MgO and low in Al_2O_3. The amount by which it differs from the curves of the variation diagram for some of the subprovinces is shown in Table 1. It is fairly near the Little Belt rocks both chemically and mineralogically.

SUBPROVINCE OF HIGHWOOD PEAK

The stock of Highwood Peak is made up of monzonite, quartz syenite, and microshonkinite and is very different from the other stocks of the Highwood Mountains. The analyses of the monzonite and syenite are plotted on the variation diagram (Fig. 1) and are marked P_1 and P_2.

TABLE 1.—*Amount by which the quartz latite departs from the variation curves of other petrographic provinces*

	San Juan	Little Belt	Absaroka	Highwood
SiO_2	+1.0	+2.5	+5.	+8.
Al_2O_3	−3.0	−1.2	−5.	−3.2
FeO	− .8	+ .8	+ .8	−1.2
MgO	+1.5	+ .4	+1.0	+1.0
CaO	− .3	− .5	+ .4	−1.2
Na_2O	− .7	−1.0	−1.2	− .4
K_2O	+1.0	0	0	−3.6

They are richer in SiO_2 and poorer in FeO and K_2O than the rocks of the shonkinite group and are not far from the rocks of the Little Belt subprovince.

The age of the Highwood stock relative to that of the other subprovinces is unknown.

HIGHWOOD SUBPROVINCE

The mafic phonolite and nearly all the intrusive rocks of the Highwood area except the Highwood Peak stock and the alnoites are of about the same age and are related in their mineral and chemical compositions. They form a distinct subprovince, which has been called the Highwood subprovince. The rocks of this subprovince rarely contain plagioclase or hornblende and in no case quartz or hypersthene. They are shonkinites, mafic phonolites, nepheline syenites, and syenites. Leucite, analcime, and pseudoleucite are common in the mafic rocks, especially in the fine-grained rocks. The numerous analyses of these rocks are plotted on a variation diagram in Figure 1, and they fall on or near regular variation curves. The Highwood rocks and some of the rocks of the Bearpaw Mountains are richer in K_2O and poorer in SiO_2 than those of any of the other subprovinces of central Montana, and these two groups are the only ones that contain no quartz-bearing rocks.

A triangular diagram of the norms of the rocks of the Highwood subprovince is shown in Figure 2. In this diagram the lines are long and slope to the left, as would be expected from the lack of anorthite in the feldspar, the low silica content of the rock, and abundant mafic minerals.

The Highwood subprovince is younger than the quartz latite and is separated from it by a period of extensive erosion. Its relation to the other subprovinces is not known.

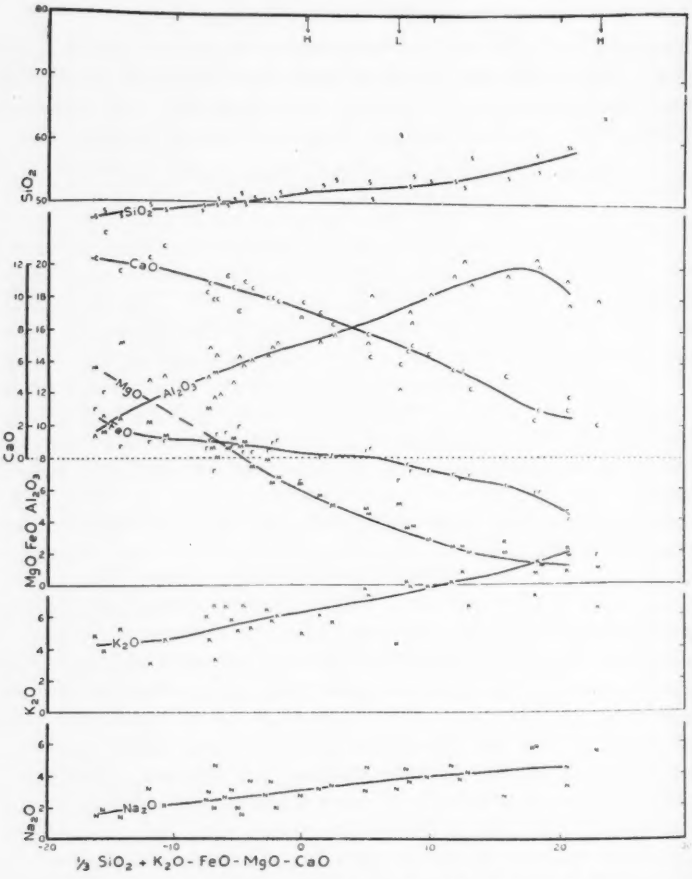

FIGURE 1.—*Variation diagram of the rocks of the Highwood subprovince*
H. rocks from the Highwood Peak subprovince.
L. rocks from the quartz latite subprovince.

ALNOITE SUBPROVINCE

The alnoite and monticellite peridotite of Haystack Butte make a fourth subprovince which is very rich in CaO and poor in SiO_2.

ORIGIN OF THE PRIMARY MAGMA OF THE SUBPROVINCES

Larsen (1940) has shown that a primary magma must have changed in depth to yield the parent magmas of the various subprovinces of

Central Montana and that these parent magmas changed nearer the surface to yield the rocks that we see.

Since in the differentiated laccoliths and the headed dike the original magma was mafic and the felsic rocks which are like the other felsic

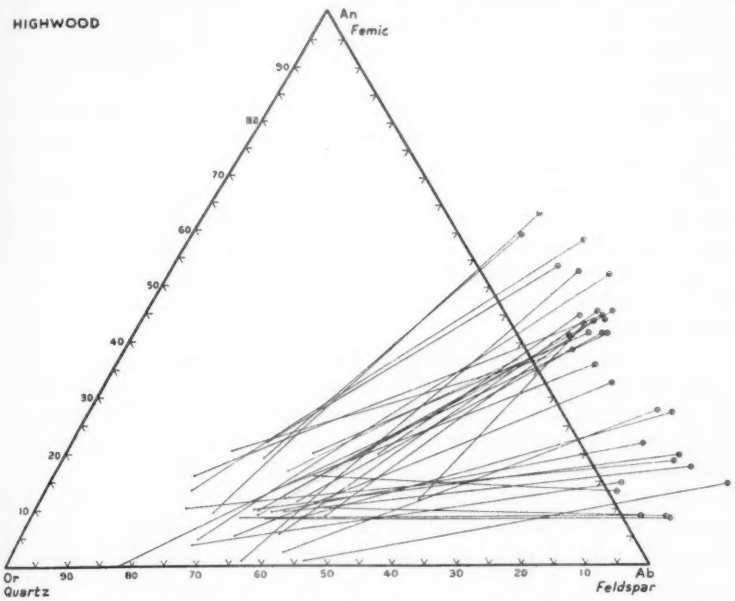

FIGURE 2.—*Triangular diagram of the norms of the rocks of the Highwood subprovince*

Dots for Or—Ab—An.
Circles for quartz—feldspar—femic.
Circles outside the triangle show SiO_2 deficiency.
Lines join the dots and circles for a rock.

rocks of the subprovince were derived from it, it is believed that a mafic rock was the parent magma of the subprovince. Variation diagrams for most petrographic provinces for which there are analyses of a wide variety of rocks stop rather abruptly at both ends. There is often a concentration of analyses near the ends. The few analyses beyond the points where analyses are abundant represent small abnormal bodies, and the analyses do not fall very near smooth curves. This position at the mafic end beyond which analyses are few and erratic is taken to represent about the original magma of the subprovince.

The quartz latite and the Highwood Peak subprovinces have a small variety of rocks, most of which are rather felsic. They do not yield

enough data for a study of the subprovinces. The rocks of both these subprovinces have quartz and plagioclase as essential minerals, and they must belong to subprovinces that are between the lime-alkalic rocks and the Highwood subprovince of potash-rich rocks. The three analyses of rocks from these subprovinces do not fall very near the variation diagrams for any of the other subprovinces of Montana. They are something like the Little Belt subprovince both in the mineral and chemical composition.

The alnoite subprovince is extremely rich in CaO and poor in SiO_2. It represents a very small local intrusive. Local assimilation of limestone seems to be the easiest way to account for these lime-rich rocks.

The rocks of the Highwood subprovince contain very little plagioclase and no quartz. They are richer in K_2O and poorer in SiO_2 than those of any of the other subprovinces of Central Montana, with the exception of some of the rocks of the Bearpaw Mountains. Analyses of 36 rocks from this subprovince are available and are plotted on a variation diagram in Figure 1.

To test the possibility of forming the Highwood magma from an ordinary basaltic magma, the smallest amount of material that can be added to and the smallest amount that can be subtracted from the San Juan basalt and the average plateau basalt of Daly to yield the Highwood magma have been calculated and are listed in Table 2.

The material that must be added is not a reasonable material to add, even by selective assimilation, and the formation of the Highwood magma from a basaltic magma by assimilation alone is improbable.

The amount of material that must be subtracted from a basalt to yield the Highwood magma is large. In terms of minerals it would be labradorite, diopside, and hypersthene with some quartz or olivine. Both the basalts and the mafic phonolite of the Highwood Mountains indicate that near the surface plagioclase, olivine, and augite would crystallize. Pressure would favor the formation of hypersthene in place of olivine, and slow, deep crystal differentiation may account for the character of the magma. The assimilation of limestone followed by crystal differentiation would increase the amount of crystals that would need to be settled, which would in that case be olivine, diopside, and plagioclase.

The very high content of BaO and SrO in the Highwood rocks cannot be accounted for by crystal settling alone. In the Highwood province MnO is moderate, TiO_2 low, and P_2O_5 rather high. These offer no difficulties.

DIFFERENTIATION WITHIN THE HIGHWOOD SUBPROVINCE

The analyses of rocks from the Highwood subprovince when plotted on the type of variation diagram proposed by Larsen (1938) fall near

regular curves as shown in Figure 1. The analyzed monzonite and syenite from the Highwood Peak subprovince and the quartz latite are also plotted to show how they differ from the other rocks. On this diagram the total iron + MnO is calculated as FeO, the BaO and SrO are added

TABLE 2.—*Composition of the smallest amount of material that can be added to or subtracted from the San Juan basalt and the average plateau basalt of Daly to yield the Highwood magma*

	San Juan magma	Plateau basalt	Highwood magma	Added to San Juan	Added to Plateau basalt	Subtracted from San Juan	Subtracted from Plateau basalt
SiO_2	53.8	51.2	48.7	34.8	47	55.8	52.4
Al_2O_3	17.2	14.7	12.7	0	11	19.2	14.9
FeO	9.8	13.8	9.0	6.6	0	10.2	14.6
MgO	5.8	7.0	9.2	18.2	11	4.2	6.8
CaO	8.4	9.9	11.0	18.6	11½	7.2	9.6
Na_2O	3.4	2.7	4.4	7.1	2½	2.9	2.9
K_2O	1.6	.7	5.2	15.2	14	0	0
BaO	.06		.5				
SrO	.03		.2				
MnO	.15	.17	.1				
TiO_2	1.4	2.2	.6				
P_2O_4	.4	.3	.8				
			NORMS				
Q						9	
ab						25	25
an						36	27
di							17
hy						29	19
ol							12
cor						1	
Mg/FeO						0.7	0.5
Amount (%)				27	37½	59	88

to the CaO, and the sum of the major constituents is calculated to 100 per cent. The horizontal scale is taken as ⅓ SiO_2 + K_2O-FeO-MgO-CaO.

Qualitatively the minerals of all the rocks of the Highwood subprovince are much the same. The mafic phonolites and shonkinites have augite, olivine, sanidine, and nepheline with some biotite, leucite, analcime, or pseudoleucite. The nepheline syenites have augite, biotite, sanidine, and nepheline with rare sodalite and hornblende. Syenites without nepheline are found only in the dikes. In the nepheline syenites and syenites the augite phenocrysts contain some acmite. In the porphyritic rocks high in mafites augite, olivine, and a little biotite crystallized early, and some leucite, analcime, or feldspar crystallized later.

Hurlbut and Griggs (1939) have shown that the laccoliths, and Buie (1941) that the headed dike, differentiated in place by the settling of much augite, some olivine, and a little biotite. In the headed dike some soda leucite or pseudoleucite floated to the upper part of the body. In

the differentiated bodies there are few inclusions, and there is good reason to conclude that assimilation of foreign material was insignificant.

In order to test the theory of crystal settling quantitatively for the Highwood subprovince, the values of the oxides were read for a number

TABLE 3.—*Composition and least amount of material that can be removed from the magmas of the Highwood subprovince to move the chemical composition along the variation diagram of the subprovince, and calculated minerals that must be removed*

Move from position to	−15 to −10	−10 to 0	0 to 10	10 to 15	15 to 20
SiO_2	45.2	42.7	45.8	36.0	35.6
Al_2O_3	0	3.7	6.0	0	27.6
FeO	13.9	11.1	11.0	19.4	14.0
MgO	26.5	25.5	15.0	16.5	4.5
CaO	12.0	16.1	19.4	24.2	13.7
Na_2O	0.7	0	0	0.5	3.0
K_2O	2.5	0	0	0.2	0
Amount removed	16½	25	23½	8	12
CALCULATED MINERALS TO BE SUBTRACTED					
Diopside	8.0	16.1	18.5	7.9	6.0
Acmite				0.8	3.0
Olivine	8.0	9.6	3.0		
Biotite				2.0	
K_2O+Na_2O	0.5				
Al_2O_3		0.9	1.4	def. .3	3.3
SiO_2 deficiency	0	1.6	0	2.0	.4
MgO/FeO (total iron)	1.9	2.3	1.4	0.8	0.3
Percentage of original magma remaining	84	63	48	45	39

of positions on the variation diagram, and the least amount of material that can be subtracted from the mafic rocks to form the more felsic rocks was determined and is given in Table 3. The extreme mafic rocks of the lower horizons of the laccoliths are known to have had crystals added to them, but this does not change the calculations. In these calculations Na_2O was substituted for K_2O in molecular proportions, as it is known that in the paulopost processes, such as the alteration of the nepheline, there was some replacement of one alkali by the other. Some of this replacement may have taken place during the magmatic stage by gas transfer (Fenner, 1926, p. 715-744). The results of these calculations and a calculation of the minerals that must be removed, using as the augite the analyzed augite from Square Butte, are given in Table 3.

Table 3 shows that the magma can be changed from −15 to 10 (from the shonkinites and mafic phonolites to the nepheline syenites) by the removal of diopside of the composition of the diopside in the shonkinite

of the Square Butte laccolith and olivine of about the composition of the olivines in the rocks. Olivine and diopside are in about equal amounts at the mafic end, and the proportion of olivine decreases in amount as the magma becomes poorer in mafic minerals. These are the minerals and in about the correct proportions that the field and laboratory data show were settled in the differentiated bodies. Some alkalies and Al_2O_3 and some deficiency of SiO_2 appear in the calculations but they probably result in part from the imperfection of the data and in part from settling of some biotite and other constituents and the floating of soda leucite or pseudoleucite. Gas transfer or some similar process may have had some effect. The laccoliths, the stocks, the dikes, and the lavas fit the same variation diagram, and the same process of differentiation, chiefly by crystal settling of diopside and olivine, must have brought about the differentiation of these bodies as well as that of the laccoliths and headed dike.

To change the magma from position 10 to position 15 requires the removal of diopside with some acmite and biotite. These are the minerals that form phenocrysts in that range. The large deficiency of SiO_2 may result from the inaccuracy of the data or from gas transfer.

According to the calculations, to move the magma from position 15 to position 20 would require the removal of an iron-rich augite-diopside and Al_2O_3. The rocks indicate that the pyroxene and biotite would be minerals likely to be removed. In their range the curves of the variation diagram are not very reliable in this range, and the calculation is uncertain.

Magmatic differentiation within the Highwood subprovince must have been in large part by crystal fractionation of the type shown by the laccoliths and headed dike of the subprovince. The extremely mafic rocks had about equal amounts of olivine and pyroxene added to them. The very mafic nepheline syenites were derived from the shonkinite magma by the settling of much diopside, some olivine, and a little biotite and leucite. The further loss of diopside and possibly biotite and the addition of some leucite yielded the nepheline syenites. Further loss of acmitic diopside and biotite yielded the felsic nepheline syenites. The change of the magma to nepheline-free syenites must have required the addition of SiO_2, and abundant inclusions of granitic rocks that show reaction with the magma are present in the biotite phonolites. Gas transfer may have played some part in the process.

ERRATA

The following three analyses of rocks from the laccoliths were omitted from Part I of this work (Hurlbut and Griggs, 1939):

	1	2	3
SiO_2	50.11	50.00	52.30
TiO_2	.82		1.18
Al_2O_3	17.13	19.36	18.92
Fe_2O_3	3.73	3.87	2.51
FeO	3.28	2.67	3.52
MnO	tr		
MgO	2.47	2.18	1.81
CaO	5.09	4.96	4.12
Na_2O	3.72	3.63	2.57
K_2O	7.47	8.52	10.33
H_2O-		.46	
H_2O+	4.47	3.53	1.96
P_2O_5	.67		.09
S	.08		.06
Cl	.07		
BaO	.63		.51
SrO	.35		.16
CO_2			.09
	100.09	99.18	100.13
Less O for Cl	.02		
	100.07		
	NORMS		
or	44.48		47.81
ab	9.43		
an	8.05		9.45
lc		Partial	10.46
ne	11.08	analyses	11.64
no	.71		
di	10.20		11.71
ol	2.19		.97
il	1.52		2.28
mg	5.34		3.71
ap	1.68		
	II.″6.″2.″3		II.6.″2.2

1. Basic syenite from Palisade Butte laccolith. H. W. Foote, analyst.
2. Basic syenite from Shonkin Sag laccolith. Partial analysis by W. F. Hillebrand.
3. White syenite of Square Butte laccolith about 300 feet below top on west slope. F. A. Gonyer, analyst.

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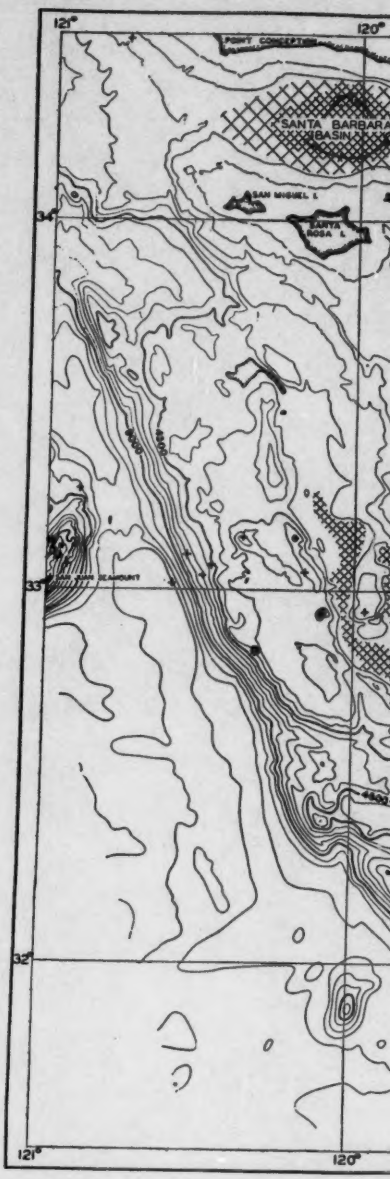

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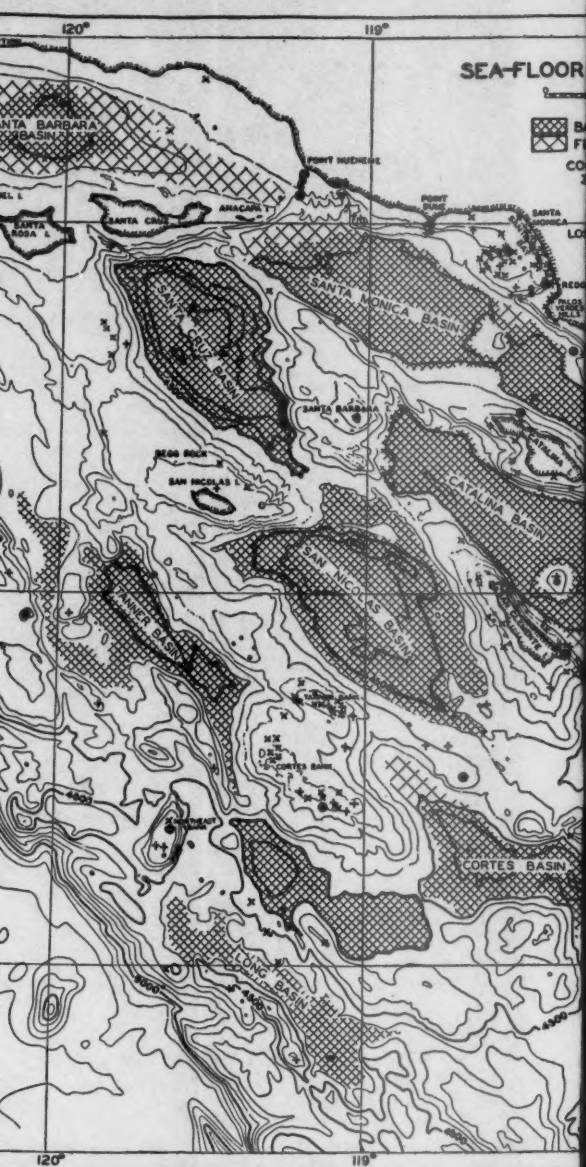

SEA FLOOR OFF SOUTHERN CALIFORNIA

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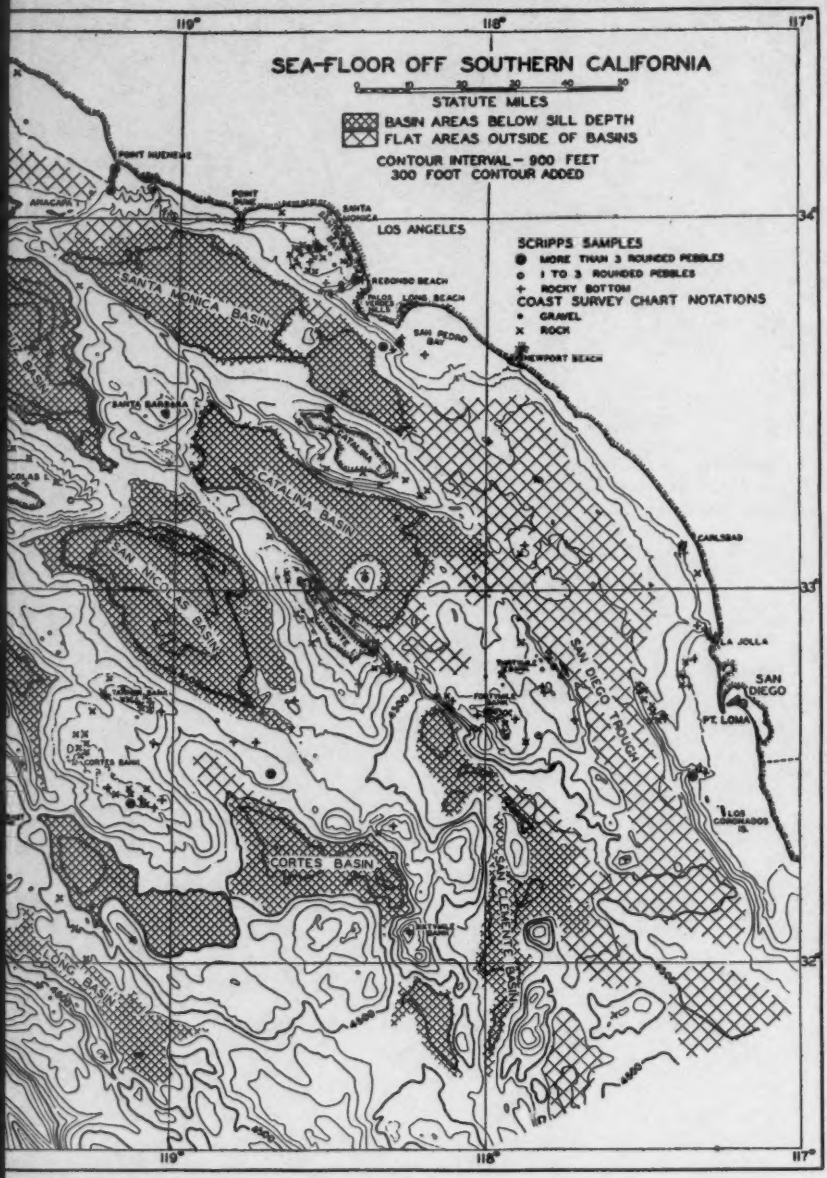
complete in the near-shore zones of the continental shelf and are some
ours are taken from Shepard and Emery (1941, Chart I).



LOOR OFF SOUTHERN CALIFORNIA

ch rock bottom and gravel bottom were found by dredging from scientific vessels or were Note that the various symbols give some indication of the significance of the samples. re zones of the continental shelf and are somewhat generalized in places where crowding pard and Emery (1941, Chart I).

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NONDEPOSITIONAL PHYSIOGRAPHIC ENVIRONMENTS OFF THE CALIFORNIA COAST

BY FRANCIS P. SHEPARD

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ABSTRACT

Recent explorations on the Scripps Institution vessel have confirmed the impression obtained from previous work that there are extensive areas off the California Coast where deposition is either very slow or nonexistent. Dredging and coring operations show either rock bottom or a very thin sediment cover on most of the deep banks off southern California, on many steep submarine slopes, on the walls and even on the floors of submarine canyons, and on the outer portions of the continental shelves.

Depth seems to have little bearing on these occurrences. Further possible evidence of absence of important deposition comes from the finding of sand and gravel in very deep portions of submarine canyons where mud should be the chief sediment. Sand was discovered even in portions of the troughs and basins off southern California at depths ranging around half a mile. This sand may be significant because the chief sediment being supplied to the deep areas at present, insofar as can be determined, is silt and clay. The importance of bottom currents and of submarine mud flows in preventing deposition is discussed.

INTRODUCTION

The idea still seems to prevail that deposition of sediment is taking place over the greater part of the sea floor bordering the continents. However, a recent symposium (Trask, 1939) brought together considerable evidence from the continental shelves in various parts of the world suggesting that deposition is by no means universal. During 1938 investigations on the *E. W. Scripps* greatly extended earlier information (Revelle and Shepard, 1939) concerning sedimentation conditions off the California coast. The area off southern California, where most of the work was accomplished, proved a particularly fitting place to look for nondepositional marine surfaces because it represents so many different environments. They include narrow continental shelves and insular shelves; relatively deep basins and troughs; banks and "seamounts" [1] with summit depths varying from a few feet down to 2 miles below sea level; escarpments with slopes up to 100 per cent; and submarine canyons.

Extensive dredging and coring of the bottom in this southern area have suggested that of all the different environments only the basins, troughs, and slope bases are receiving appreciable quantity of sediment under present conditions. There is even evidence that finer sediment by-passes portions of the inner basins and troughs. Investigations off central and northern California, partly of earlier date, have also indicated the absence of sediment accumulation over an extensive area. The evidence for this nondeposition, and the possible underlying causes are discussed in the present article.

ACKNOWLEDGMENTS

The work on which this report is based was made possible largely through a grant from the Penrose Bequest of the Geological Society of America and through the active co-operation of staff members of the Scripps Institution of Oceanography. The California Fish and Game Commission and the U. S. Coast and Geodetic Survey also provided opportunities for dredging operations by the writer. The co-operation of Roger Revelle, K. O. Emery, and Robert Dietz was of high value. The writer

[1] The term "seamount" was introduced by the U. S. Coast and Geodetic Survey to designate a mountain mass rising above the deep sea floor and is used here in contrast to "banks" which rise above a shelf or zone of intermediate depth.

wishes to express sincere appreciation to these individuals and organizations.

EVIDENCE OF NONDEPOSITION

ROCK BOTTOM

Of the various lines of evidence suggesting nondeposition of sediments the most significant is, of course, the discovery of rock bottom. Reports of this type of bottom have come from numerous localities off the California coast (Pl. 1). These reports were chiefly obtained by sounding operations of the U. S. Coast and Geodetic Survey. The finding of fresh scratches on the sounding lead is one basis for Survey reports of "Rocky". Such scratches suggest the presence of rock bottom since the lead must have come in contact with some hard firm substance. Gravel could not produce such markings although large boulders could scratch the lead, so that the existence of ledge rock is not proven by such findings. However, absence of marine deposition, except in the littoral zone, is indicated by a bouldery bottom as well as by ledge rock. The other basis for the report of rock bottom by the U. S. Coast and Geodetic Survey is the finding of angular rock fragments in the tallow cup at the base of the sounding lead or in the jaws of the small telegraph snapper which is sometimes used. The presence of these rock fragments does not prove the absence of deposition since stray pieces of rock are introduced into an area by various flotation methods. In some areas which are free from any other appreciable source of sediments and where the currents are favorable, small rocks dropped from kelp may become an important factor.

The dredging operations by the writer have produced more definite evidence of rock bottom. Dredges, such as shown in Figure 1 of Plate 2, were used. Numerous rock fragments were recovered, many so large that chance introduction by kelp would be improbable (Pl. 2, fig. 3). The rocks dredged from slopes may be talus or slide rocks derived from a higher position. However, the large fragments from the tops of banks or from flat shelves were probably *in situ*, and some of the fragments from slopes were clearly ledge rock since they showed fresh fractures. A further indication of ledge rock was the firmness of the rock masses on the bottom. Frequently the dredge caught on bottom hard enough to stop the progress of the vessel. Great difficulty was encountered in breaking off fragments, and several dredges were lost in the attempt.

Finally, the existence of kelp off a coast is an almost certain indication of rock bottom. This marine plant grows only where there are rocks of sufficient size for the holdfasts to take root. Insofar as the writer knows, the kelp beds on the California coast are found on ledge rock where little sediment exists.

GRAVEL BOTTOM

Streams that enter the ocean with high velocity may introduce gravel, or waves working on cliffs containing the proper type of rock to form gravel may develop a potential marine conglomerate. However, investigations by the writer along the California coast seem to indicate that this gravel is kept in the zone of violent wave action near the coast and under storm conditions is normally piled high on the shore. Evidence compiled by Johnson (1919, p. 93-94) showed that rock ballast dumped miles out from land is sometimes carried shoreward. Accordingly, the discovery of gravel deposits on the shelf many miles from shore or in other areas still more remote from sources suggests that deposition is not taking place where the gravel is found.

Even if unusual wave conditions do allow the movement of gravel to the outer portion of the shelves, transportation to the outlying banks off southern California is impossible. The gravel obtained from many of these banks (Pl. 1) indicates the absence of appreciable deposition. Had the gravel been introduced by kelp, accumulation of other sediment at any appreciable rate would mask the occasionally introduced pebbles.

SANDY BOTTOM IN DEEP WATER

Layers of clean sand have been found in some of the basins off southern California where the predominant sediment introduced from the land is of much finer grade (Revelle and Shepard, 1939, p. 279). The following three possible explanations for this sand can be offered: (1) that deposition is not taking place and that the sand is residual; (2) that the fine sediments are kept in suspension allowing accumulation of only the coarser fractions; and (3) that attrition due to currents causes the concentration of the sandy portion of the sediment in some portions of the basins.

The existence of coarse sand on the outer edge of the continental shelves may be an indication of nondeposition, particularly if finer sediment is found nearer shore. In connection with his work off the Atlantic Coast Stetson (1938, p. 40) found that "the well sorted sands at the break in slope are probably residual from Pleistocene conditions. . . ." The present writer and his collaborators have produced evidence for the same view in sedimentation studies off both the east and west coasts (Shepard and Cohee, 1936, p. 455; Shepard and MacDonald, 1938, p. 213).

TOPOGRAPHIC INDICATIONS

Where deltas are built out into fiords or lakes with steep margins it is possible for foreset slopes to develop with a declivity up to about 40 degrees (Twenhofel, 1932, p. 604). This, however, is very exceptional

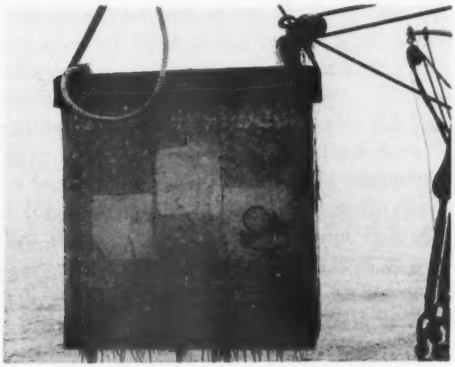

FIGURE 1. ONE OF THE TYPES OF DREDGES
Used to obtain rock from the sea floor off the California coast.

FIGURE 2. WAVE-CUT TERRACE
Exposed at low tide off La Jolla, California.

FIGURE 3. ROCKS OBTAINED IN A DREDGING OFF SOUTHERN CALIFORNIA
In water 3600 feet deep. Note the combination of large angular blocks of shale and rounded pebbles and cobbles of igneous rock.

ROCK DREDGE, WAVE-CUT TERRACE, AND ROCK SAMPLES

and ordinary marine deposition slopes are much gentler. According to charts the slopes in front of large deltas on the shelf average only 0.7 per cent. The continental slopes are much steeper than this. The writer constructed 500 profiles off all shores of the world. The average slope of the steepest portions of each of these profiles is 8.6 per cent. The slopes appear to have been flattened where they have been built forward by deposition from large rivers. For example the continental slope outside the passes of the Mississippi Delta has an inclination of only 1.0 per cent. Therefore, steep submarine slopes, except in a coral reef area, indicate that they are not due primarily to outgrowth of sediments from the land, although they may be somewhat masked by sediments. Furthermore, if the slopes are located in places with no available source of clastic sediments, they would likely be nondepositional surfaces.

Where marine slopes are straight as well as steep, it seems highly probable that they have not been greatly affected by deposition. The forward building of a slope should result in bulges where active deposition occurs. Similarly the sharp V-shape of submarine canyons and of a few submarine fault valleys suggests the absence of any great amount of fill subsequent to their development.

NONDEPOSITION ON CONTINENTAL AND INSULAR SHELVES

GENERAL CONSIDERATIONS

The term continental shelf here refers to shallow-water platforms,—less than 100 fathoms deep—which lie adjacent to the land; the definition does not include the Basin and Range topography of the greater part of the area shown in Plate 1. Similarly, insular shelves refer to the shallow-water platforms around the islands. Numerous bottom indications from almost all parts of these shelves have been obtained by the U. S. Coast and Geodetic Survey. While information from this source is fairly extensive, the writer's dredging operations on the shelf were not so numerous as in some other environments. However, dredging was undertaken on portions of the shelves off San Diego, off Long Beach, in Santa Monica Bay, off Point Sur, in Monterey Bay, and off Punta Gorda. The insular shelf off Catalina Island was dredged in many places. Further information came from the finding that canyons which cut into the shelves are commonly rock-walled.

ROCKY ZONES NEAR SHORE

The California coast can be divided into three distinct types: (1) cliffed coasts where the waves have eaten into the rocks of the headlands or mountain ranges terminating at the shore; (2) cliffed coasts where the sea has cut into recent unconsolidated deposits and has in general de-

veloped a straight shore line; and (3) lowland coasts where the sea comes into contact with a coastal plain or delta. Rocky bottom is almost invariably found directly off the first of these types. On the other hand, off the second type of coast the near-shore zones[2] rarely have rock, and no cases are known off the third type.

The near-shore rocky zones are visible in many places at low tide (Pl. 2, fig. 2). Elsewhere when the sea is calm and the water clear the rocks may be discerned from the tops of the cliffs. In many places isolated stacks rise above the surface. The presence of kelp, which is thought to grow only on rocky surfaces, also indicates bare rock. Kelp grows around or adjacent to almost all the rocky headlands along the California coast, such as Point Loma, Point La Jolla, the Palos Verdes Hills, Point Dume, Point Sur, Point Lobos, Monterey Peninsula, and Cape Mendocino. These zones of rocky bottom can be traced on charts, either by kelp or bottom notations, out to depths of 60 to 120 feet and for distances of 1 or 2 miles from the shore. In places even greater depths and distances are found. Various maps of bottom character show the approximate size of these rocky areas (Revelle and Shepard, 1939, Fig. 1; Shepard and MacDonald, 1938, Fig. 2; Shepard and Wrath, 1937, Fig. 1). However, these zones are not devoid of sediment; actually patches of sand are scattered over the rock surface. This sand is probably of transitory character rather than a permanent sediment accumulation.

SHELF MARGINS

The near-shore rock surfaces, previously discussed are examples of wave-cut terraces. However, the zone at or near the outer margin of the continental shelves, having abundant evidence of nondeposition, does not conform with the theoretical concept of wave-built terraces, commonly assumed to have formed the outer shelves. There are reports from many parts of the world of either coarse sediment or of rocky bottom both at and near the outer margin of the shelf (Shepard, 1932, p. 1038; 1939, p. 223) so that the evidence to be presented is not unique for the California coast.

The rocky outer zones of the shelves are reported by the U. S. Coast and Geodetic Survey off all of the types of California coast, even to a limited extent off the lowlands, as for example, on the shelf off the alluvial plain south of Los Angeles. The authenticity of some of these rocky zones was established by dredging operations on the *E. W. Scripps*. Large slabs of rock were obtained from the outer shelf off Long Beach, in Santa Monica Bay, off the western edge of the Santa Monica Moun-

[2] Meaning roughly zones within a half mile of the shore line.

tains, off Point Sur, and in Monterey Bay. Most of this material is clearly of local derivation.

Coarsening of sediment at the edge of the shelf was observed in part of Santa Monica Bay (Shepard and MacDonald, 1938, Fig. 3b) and Monterey Bay (Galliher, 1932, Pl. 3). To this evidence may be added many U. S. Coast and Geodetic Survey reports of gravel and coarse sand along the outer shelves. In collecting samples around Catalina Island the writer found a coarsening of sediment at the break in slope in numerous places both on the exposed and semiprotected sides of the island (Shepard and Wrath, 1937, p. 43). Off Avalon Cove where quiet waters prevail most of the year coarsening at the break in slope was shown by the selective sorting of calcareous shells, largely Foraminifera, which cover this insular shelf. On the exposed side of the island dominantly clastic sediments also showed a distinct coarsening at the edge. Furthermore, the U. S. Coast and Geodetic Survey found rock bottom in a considerable number of places along the shelf margin.

BARE WALLS AND FLOORS OF SUBMARINE CANYONS

The nature of the walls and floors of the submarine canyons is discussed at length elsewhere (Shepard and Emery, 1941, p. 86-89) so that only partial consideration need be given here. A total of 21 canyons along the California coast have now been dredged, and rock has been discovered in all but four. While much of this rock was of relatively soft Tertiary sedimentary material, it serves to show that recent sediments are not covering the canyon walls. On the other hand, most dredging on the walls netted considerable quantities of mud and sand. These sediments were even found on walls having a 50 per cent slope. This combination of bare rock and sediment seems to indicate that the sediment does not accumulate permanently, but is lodged there until it acquires sufficient weight to start a slide or mud flow down into the canyon bottom. Otherwise, in the long interval which appears to have intervened since the canyons were submerged (Shepard and Emery, 1941, p. 126-128) sediment should have cloaked the walls quite completely. Dredging results seem to indicate that more rock is exposed on these walls than on the walls of typical land canyons on the adjacent coast.

Preliminary examination of the California canyon floors gave the impression that most of them were receiving sediment (Cohee, 1938). However, more complete study with improved equipment showed that only those canyons which head at some distance from the coast contain appreciable fill. The muddy floor sediment of those canyons which extend in close to the coast was found to consist of only a thin cover. For example coring with the Emery-Dietz device along the axis of

Monterey submarine canyon established the absence of any appreciable mud fill from the head out to depths of 5000 feet. The bottom was hard-packed sand, gravel, or rock. Dredging brought up several types of rock from the floor of this canyon. Numerous tests in other canyons heading near the coast showed conditions similar to those in Monterey Canyon. On the other hand those canyons terminating landward at some distance from the coast were found to have at least a 10-foot fill of mud. Whether or not this discovery shows that the outer canyons are being gradually filled remains undecided. However, the evidence obtained by Stetson (1936, p. 356) from the east coast canyons suggests continuous fill at least since the Wisconsin glacial epoch. On the other hand the general V-shape, indicated by soundings in the canyon heads, suggests that deposition has not produced any great fill even in those canyons which lie at a considerable distance from the coast. Furthermore, the 3 feet of postglacial fill in the canyons off the New England coast (Stetson, 1936, Table 1 and p. 356) shows that a very considerable period would be required in order to greatly modify the V of the canyons.

The flat bottom found in some of the canyons off the California coast is no proof that there has been recent deposition. Monterey Canyon was found to have a floor half a mile across in depths of 5000 feet, but a core taken near this carefully measured section showed only a thin film of mud over sand which graded down into gravel containing pebbles 5 centimeters in diameter. Along with this coarse clastic debris, numerous shell fragments were found. The abundant shells and gravel seem to prove that the material is residual from a time when the canyon stood much higher in relation to sea level. Thus unless there has been a catastrophic submergence in recent times the narrow valley flat has been kept clean of sediment for a very considerable period.

BARE SLOPES OF SUBMARINE ESCARPMENTS

The various escarpments off the coast of southern California, illustrated by the contours in Plate 1 (*see also* Shepard and Emery, 1941, Chart I) are so steep that it is natural to expect that sediment would only lodge on them temporarily. Notations concerning the bottom on these slopes obtained by the U. S. Coast and Geodetic Survey are not very numerous but they do show a large percentage of rocky bottom. A notable place for such observations is on the escarpments bordering the basin between Catalina and San Clemente islands. The writer has also dredged a number of these escarpments bringing up considerable quantities of rock, although some places failed to produce any rock.

In the light of present knowledge, at least the steep upper portions of these escarpments, which are thought to be fault scarps (Shepard and

Emery, 1941, p. 71), should be considered as probable nondepositional surfaces but the evidence is not yet conclusive. In this connection the work of Kuenen in the Dutch East Indies should be considered. Coring by Kuenen (1934, p. 70) on slopes up to 34 degrees failed to produce any appreciable quantity of rock. However, since most of the cores were less than 1 meter in length, it is always possible that the submarine slopes were covered with a thin veneer of sediment which would have been pierced if longer cores had been obtained. Furthermore, dredging operations because of the greater area covered have far greater chance of encountering rock outcrops.

ROCKY BANKS AND SEAMOUNTS

Off the coast of southern California there are a total of 77 submarine eminences rising over 1000 feet above their surroundings. The largest of these, which has been called San Juan Seamount, rises approximately 10,000 feet above the abyssal depths which surround it. Most of the others, however, have much less relief and rise above the "continental borderland" [3] where the bottom is at a level more closely allied to that of the continent than to the deep ocean floor. Most of these masses are referred to as banks and have rather flat tops. The summits of these submarine mountains are extremely variable in elevation. On the continental borderland the banks vary from depths of a few feet down to about 4500 feet. On the deep-sea floor the seamounts have summit depths from 1800 feet down to 11,400 feet.

The bottom character of many of the banks was determined by the U. S. Coast and Geodetic Survey. The writer dredged 14 of the banks off southern California as well as San Juan Seamount. As a result, information from most of these features is available. There seems to be little doubt that most of the elevations, at least off this coast, are swept free from mud. Sand, consisting of Foraminifera and other calcareous organisms, masks portions of ma. y of the banks which have depths of less than 600 feet, but the banks in general were found to have bare-rock surfaces, and even the shoaler banks have some outcroppings of rock. The dredge generally caught on ledge rock while being pulled across one of these submarine banks. On only one elevation did the dredge encounter mud and fail to give any signs of hitting rock bottom.

The rocky bottom is not confined to the tops of banks and seamounts. In several cases where dredging failed to break loose any rock on the summit of a submerged mountain, the dredge was pulled up the moun-

[3] "Continental borderland" is a term applied to the sea floor off the southern California coast and off adjacent portions of Lower California where the topography is of the Basin and Range character found on the adjacent lands.

tainside, and rock was encountered 1000 feet or more below the summit. Rock was recovered from the east wall of San Juan Seamount at a depth of 5000 feet, and a small dredge was wedged so securely in the rock on the northwest side at 9000 feet that it could not be dislodged. An attempt to secure a core at 9750 feet on the north side resulted in a badly bent nose and tube. Here, also, rock must have been encountered or at least a hard bottom free from recent sediments.

Even more surprising was the indication of nondeposition on the deep-sea floor at 11,800 feet about 300 miles southwest of the coast of southern California. An attempt was made to obtain a core in this area, where the depth is 2000 feet less than that existing about 60 miles distant on either side. A bent tube and bent core nose showed that the core barrel hit a hard bottom at the 11,800-foot depth. Fragments of manganese oxide were recovered stuck inside the valve, and a trace of red clay adhered to the core barrel. On the other hand in the deeper water to the north and south the core barrel penetrated about 11 feet into red clay. These findings suggest that even the elevations which rise slightly above the deep ocean floor might be negative sedimentation areas.

Not as much is known regarding the banks and seamounts off central and northern California. The U. S. Coast and Geodetic Survey sheets indicate rocky bottoms on some small banks. Large fragments of rock were also obtained by the writer from one bank off Point Sur. At a depth of 5800 feet near the summit of Davidson Seamount (Shepard and Emery, 1941, Chart II) the U. S. Coast and Geodetic Survey indicate rocky bottom.

The nature of the rock obtained from these various submarine hills will be discussed fully in a succeeding paper by Emery and the writer. The rocks are of considerable variety but consist more commonly of either andesite or phosphorite than of other types. However, a considerable amount of shale, limestone, and sandstone was discovered. The presence of phosphorite on so many of these banks indicates long continued absence of deposition, since phosphorite is found in the stratigraphic column in association with nondepositional surfaces. The significance of the phosphorite will be discussed elsewhere in a paper by Dietz, Emery, and the writer.

FORAMINIFERAL AND GLAUCONITIC SANDS OF SUBMARINE SADDLES

Several saddles between ridges and banks have been sampled (Revelle and Shepard, 1939, p. 257). In each case cores were obtained consisting of foraminiferal shells or glauconitic sand. Despite the thousands of feet of water which cover these saddles, mud was very scarce in the

cores. Also, in several cases rock fragments were found both at the surface and down in the sand.

It cannot be ascertained that there is no deposition on these saddles, but the presence of glauconite suggests a very slow rate of deposition (Hadding, 1932, p. 79-82; Galliher, 1935, p. 1362-1363). Also, the finding of foraminiferal sand rather than mud, which is found in the adjacent basins, shows that the finer particles are not accumulating on the saddles. The origin of the rock fragments is difficult to ascertain. Since they are of small size, the possibility of introduction by kelp should be considered.

SAND DEPOSITS OF INNER BASINS AND TROUGHS

The trough off San Diego with depths around 3500 feet and the relatively shallow basins off Palos Verdes Hills and outside Santa Monica Bay, where the water attains 2950 and 3100 feet, respectively, have been found by Revelle and the writer to contain extensive areas where relatively clean sand underlies a small thickness of mud or is even found at the surface. For the most part the coring device did not penetrate through the sand, so that its thickness is unknown. However, in other basins thin sand layers have been discovered interbedded with muds, so that it seems likely that no great thickness is represented by the sand zone in these near-shore basins and troughs off southern California.

The relatively clean sand in these deep environments can be interpreted in the three ways mentioned previously. If the sands constitute a normal basin and trough deposit, there must be periods during which large quantities of sand are carried out into the basins, making layers which may be even a foot or more in thickness. These periods must be assumed to accompany unusually great waves. However, it is hard to understand why the dominant sediment washed out to these depths at such times is sand. During typical storms along the southern California coast great quantities of mud are introduced into the sea and carried far out from the land (Revelle and Shepard, 1939, p. 271-274). Also, the sand moved seaward during storms is found to accumulate in shallow water within 1000 or at least 2000 feet of the shore (Shepard and La Fond, 1940).

If, on the other hand, current conditions exist within portions of the basins which prevent the deposition of fine sediments, allowing only the occasionally introduced sand grains to accumulate, a condition close to that of nondeposition is attained. The third possibility that the currents have locally reworked normal basin sediments causing a residual concentration of sand grains by attrition represents a type of nondeposition although the fact that the sand occurs in layers shows that nondeposi-

tion is not a lasting state. The finding of thick accumulations of muddy sediments lacking sand layers in other portions of the same basins and troughs supports either of these last two possibilities.

POSSIBLE CAUSES OF NONDEPOSITION

ADEQUACY OF SEDIMENT SUPPLY

Nondeposition could of course result from absence of supply of sediment to an area. The available evidence for the area off California, however, as has been shown previously by Revelle and Shepard (1939, p. 268-278) suggests that sediments are both introduced in large quantities into the ocean off this coast and are carried seaward for long distances. The introduction of mud into the ocean during floods is made evident by the brown color of the water extending for many miles seaward from the river mouths. This mud moves seaward largely near the surface. Probably considerable mud also moves seaward along the bottom and perhaps to some extent at intermediate depths.

The cause of sand transportation out into deep water is one concerning which few data are available. The samples appear to indicate that such transportation does take place, but observations of sand movements along the piers show that during normal winter storms most of the sand is carried out only for a few hundred feet where it lodges and is carried in again during the calm weather of the following summer (Shepard and La Fond, 1940, p. 275). Work by the Los Angeles engineering department also shows that sand is shifted seaward for a short distance in winter and returns to the beaches in summer. Possibly extreme conditions such as have not been recorded in recent years would be necessary for the seaward transportation of the sand into the basins and troughs.

EFFECTS OF WAVES

Few quantitative data are available to show whether waves can be of importance in keeping sediment from accumulating in most of the environments which have been discussed. Previous information regarding sand movements has suggested that waves do not have much cutting effect except very near the shore. On the other hand Kuenen (1939), in discussing the nondepositional surfaces at the breaks in slope on the outer edge of the continental shelf, presented evidence obtained by Vening Meinesz that submarines are considerably moved by waves at depths of 60 meters during rough weather, and he also showed how waves approaching the continental shelf have their energy concentrated near the break in slope and for an indefinite distance in along the shelf. Kuenen suggested that this factor accounts for the coarse sediment which Stetson

and the present writer had reported from the edge of the continental shelves.

POSSIBLE EFFECTS OF TSUNAMIS

Tsunamis (tidal waves) of large dimensions are unknown along the California coast, but such waves may have occurred prior to the arrival of civilized man in this region. The seismicity of the area suggests this possibility. If Kuenen is correct in attributing some stirring action to ordinary waves at the edge of the shelf, the effect of tsunamis must be far greater.[4] Tsunamis have excessively long wave lengths and therefore little decrease in velocity toward the bottom. It even seems possible that large tsunamis may have had important effects on the deep outer banks where their force would be concentrated due to the abrupt rise from greater depths.

Tsunamis may have played a very important part in keeping the banks and breaks in slope at the outside of the shelves free from sedimentary accumulation. These waves may have served as the means of carrying sand out into the basins and troughs and thus account for the sand deposits previously considered. The tsunamis would, of course, bring out large quantities of fine sediment, but violent stirring action may have prevented the deposition of the finer sediment along with the sand.

On the other hand tsunamis should not be given too much weight partly because the character and effect of their movement are still matters of uncertainty but mainly because there is no evidence that they have ever occurred off the California coast.

TIDAL CURRENTS

The nature of tidal currents is such that their velocity is increased at a break in slope or on any rise above the general level of the ocean floor. A recent study by Fleming (1938, p. 196-201, Fig. 75) illustrates this increase of current at the edge of the continental shelf in the Gulf of Panama. On the other hand the information now available on bottom currents off the California coast (Shepard, Revelle, and Dietz, 1939; Revelle and Shepard, 1939) gives little information which suggests that the tides play an important part in producing these nondepositional surfaces. Important tidal components to the currents were revealed in only two localities, and even there it could not be ascertained that the tide was the chief motivating force of the current. The absence of large tidal components becomes all the more significant since periods of spring tides were chosen for the investigations whenever possible. However, neither shelf margins nor small isolated banks where tides might play a particu-

[4] Bucher (1940) recently suggested tsunamis as a cause of submarine canyons.

larly great role have been investigated, and this may account for the lack of discovery of significant tidal currents.

NONTIDAL CURRENTS

The investigation of the bottom currents has revealed the presence of internal waves and of large moving eddies with vertical axes (to be described in a future article by Revelle and Shepard). Observations have been made along the bottom of submarine canyons, in the bottom of deep basins, on submarine escarpments, on open shelves, and on submarine ridges. The data come from depths of a few feet to 6000 feet. Detectable currents were recorded in all localities investigated except on Cortes Bank where an attempt to measure currents in 100 feet of water failed, due apparently to the strong wave motion on the bottom which wrapped the current meter around the tripod from which it was suspended. The use of this tripod allowed the measurement of the currents to be made directly on the bottom eliminating any interference from the motion of the ship.

In practically all localities regardless of depth the currents attained sufficient velocities to be capable of transporting fine material, and in some places currents were found which according to the work of Hjulström (1939, Fig. 1) should be strong enough to roll gravel along the bottom. However, there are considerable lapses in current movements which might allow all but the silt and clay to settle, and thus greater velocity would be required to set the particles again in motion. The higher velocities, with a maximum of 36 centimeters per second, would, according to Hjulström, have carried back into suspension sand particles (.05 to 2.0 mm.) but would not have disturbed silt-clay aggregates or gravel. However, as yet there are few data to prove whether the observations regarding stream transportation and erosion to which Hjulström refers, are also applicable to the ocean floor. Assuming the Hjulström values to be approximately correct, the currents which we have measured give a satisfactory explanation of the by-passing of the sediments over the nondepositional surfaces. The clean sand layers found in the basins may be due to the existing currents.

On the other hand there are some reasons to question the importance of the currents in keeping surfaces free from deposition. The currents are certainly much weaker than those which are observed in land streams where deposition is gradually building up the stream bed.[5] Also there seems to be no relationship between observed current velocity and type of bottom. The strongest current was found on the slope off the Palos

[5] These streams, however, presumably have a much heavier load of sediment than ordinarily exists near the sea floor.

Verdes Hills where the bottom is covered with mud and a thin mud cover was noted in Monterey Canyon where the second largest current was recorded. Cores show that mud has been deposited to a considerable thickness in various other localities where currents were relatively high. The currents were fully as strong in the canyons which head well out from the shore and receive sediments as in those which head near the coast and are kept clean (Shepard and Emery, 1941, p. 90). Two water samples, procured from about 3 feet above the bottom during times of maximum observed currents, failed to show any traces of suspended sediment. In both these cases the bottom was covered with sediment consisting of silt and fine sand.

MUDFLOWS AND SUBMARINE LANDSLIDES

A marine process which has been given increasing importance by recent investigators is that of mass gravity movement. The cable companies have long recognized these submarine slides in connection with the breaking of their lines on the sea floor; Milne (1897) first called them to the attention of scientists. The cable breaks have occurred both in association with earthquakes and in the absence of seismic activity. It seems likely that even those accompanying earthquakes are predominantly the result of sliding of bottom sediments. This contention is suggested by the following:

(1) On land, fault movements such as would break cables, rarely occur at the surface, but landsliding occurs on a large scale during the major earthquakes.

(2) At the time of the 1929 earthquake near the Grand Banks the cable breaks covered a territory extending for 700 miles from the epicenter (Shepard, 1931, Fig. 1). This would appear to be too great an area to be affected by surface faulting movements.

(3) At the time of the Grand Banks earthquake the cable companies reported that the cables were buried over extensive areas to such depths that they could not be recovered with deep drags (De Smitt, 1932).

Furthermore, slumping of sediments, probably in the form of mud flows, actually takes place in the canyons off the California coast (Shepard and Emery, 1941, p. 94-108, 116-118). The careful check of profiles along the heads of the canyons showed that sediments are removed from time to time and that some of these movements take place without any indication of unusual surface currents or violent wave disturbance. It seems relatively certain that slumping of the bottom has been the cause of the slides. Finally, the slopes are sufficient in many of the nondepositional environments so that sliding of saturated sediments would be expected.

CONCLUSIONS

The investigation of the sea floor off the California coast has revealed extensive surfaces where deposition of sediment is either completely prevented or is proceeding very slowly with the by-passing of the greater part of the sediment. In this category are large parts of the continental shelves, the upper portions of steep submarine slopes, the walls of submarine canyons, the floors of canyons heading near the coast, and the top and sides of most of the submarine banks and seamounts. Even portions of the inner basins and troughs along the southern California coast may be by-passed by the greater part of the available sediment.

The cause of this nondeposition is not entirely understood; but it is probably the result of internal waves and eddy currents, and to a less extent tidal currents combined with landslides and mudflows. The amount of stirring action of waves at the edge of the shelves is unknown but may be of considerable importance. Tsunamis may also have contributed in the past to the formation of these bare surfaces, particularly on the deep outer banks.

The results of these studies are not easily applied to problems of ancient sedimentary basins, but possible applications can be indicated. An unconformity in a series of marine sediments is commonly interpreted as resulting from the elevation of the area above sea level. Off California, however, the elevation of only a portion of a basin would prevent or greatly impede deposition whether or not the surface came above sea level. Also it appears that various environments off the California coast are being by-passed by sediments. Many similar environments may have existed in the ancient seas, so that it would seem advisable to make rather exhaustive studies of unconformable surfaces before concluding that they represent an emergence above sea level. Even the finding of weathered surfaces cannot safely be used as a criterion since some rock decay takes place on the sea floor and results akin to weathering are found where marine organisms have bored into the rock surfaces.

Probably these studies can be more satisfactorily applied to sedimentary basins where deep geosynclines or fault basins are involved than in areas like the Mississippi Valley region where the seas were probably quite flat-bottomed and free from the relief of the present California sea floor. However, even in the mid-continent the possibility of nondeposition arises in connection with such features as the "buried hills" around which some Paleozoic sediments accumulated. Certainly investigators would do well to keep in mind the situation now existing in the seas around the continental margins.

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